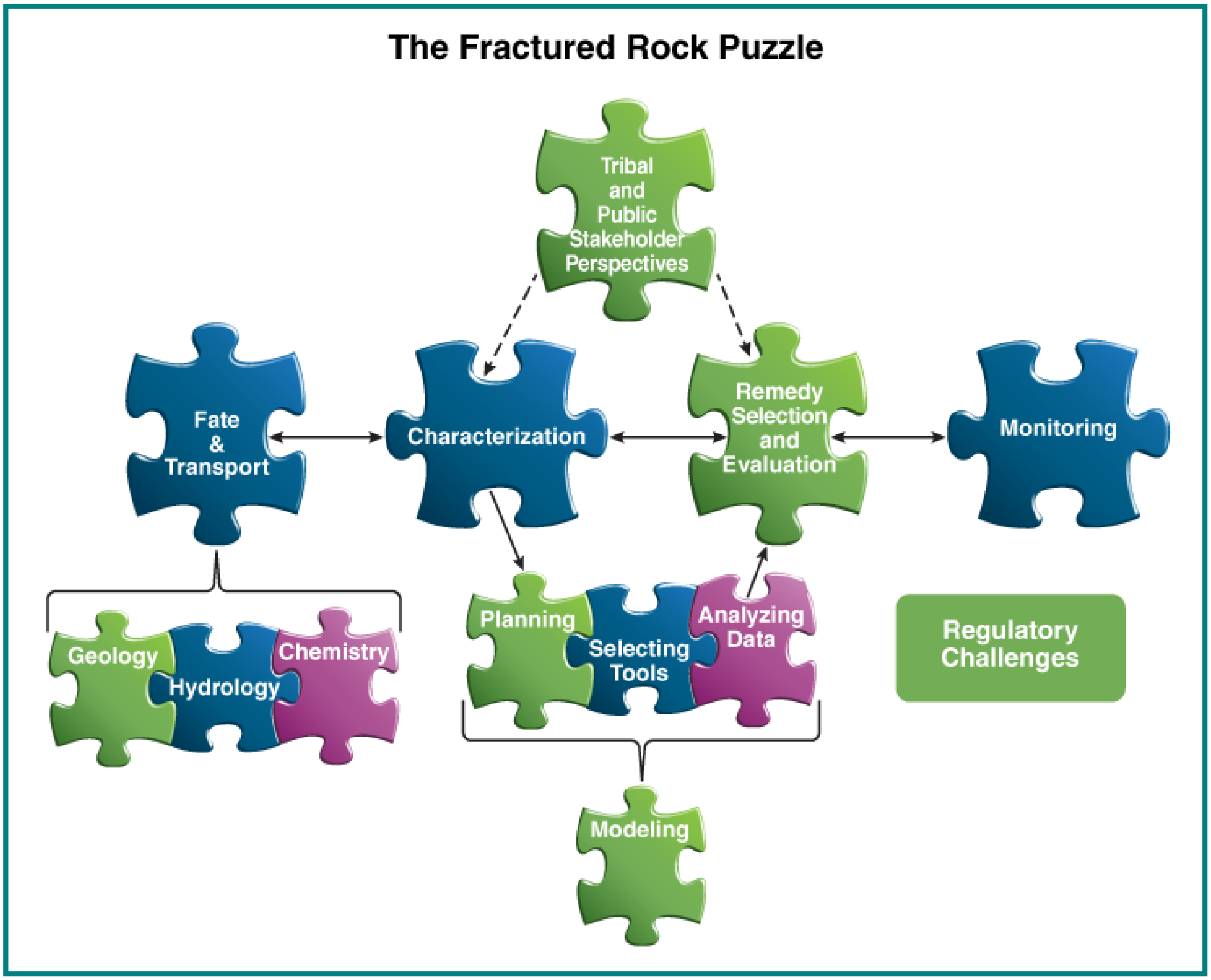
Characterization and Remediation of Fractured Rock

FracRx-1



December 2017

Prepared by
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Overview

This guidance (ITRC FracRx-1) explains the processes controlling contaminant fate and transport in fractured rock, as well as innovative approaches to managing these sites. Additionally, this guidance describes how to develop a useful conceptual site model (CSM) and how to identify strategies to remediate contamination in fractured rock. This document is part of a series of ITRC documents that present an integrated strategy to characterize, remediate, and manage contaminated sites:

- *Mass Flux and Mass Discharge*(ITRC 2010)
- *Integrated DNAPL Site Strategy*(ITRC 2011)
- *Integrated DNAPL Site Characterization and Tools Selection* (ITRC 2015b)

Contaminated fractured rock sites have often been considered too complex to be remediated, so site managers often default to simply containing the contamination. This guidance provides a high-level introduction to the unique puzzle faced when investigating and remediating fractured rock sites. With the new strategies and technologies presented here, fractured bedrock challenges that may have prevented site remediation in the past are now surmountable.

The guidance begins with a general discussion of fractured rock characteristics and a comparison of fractured rock and porous media CSMs. The guidance further introduces the parameters necessary for developing a fractured rock CSMand stresses the need for an experienced multidisciplinary team. The 21-Compartment Model is also introduced. This model is an adaptation of the 14-Compartment Model (Sale 2011) for unconsolidated materials. This model helps its users to visualize and understand contaminant storage, flux, and flow pathways in fractured rock.

Understanding contaminant fate and transport in fractured rock allows site managers to develop a robust CSM that can guide remediation. Specific geology and lithology and structure control the unique mechanics of fluid flow in fractured rock. In addition to these physical properties, chemical properties affect fate and transportand are equally important in developing the CSM.

This guidance details specific steps in solving the puzzle of fractured rock contaminant fate and transport, including:

- reviewing and refining the CSM
- defining the characterization problem
- identifying significant data gaps
- defining data collection objectives
- identifying potential tools for data collection
- developing and implementing the work plan
- managing, interpreting, and presenting the data

A downloadable and searchable Tools Selection Worksheet is provided , which was initially used in ISC-1 (ITRC 2015b). The Tools Selection Worksheet allows users to screen for tools to address specific data needs and collect qualitative, semiquantitative or quantitative data as needed. The Tools Selection Worksheet links to detailed descriptions of all the tools and to references for further information. The guidance describes how data can be managed, interpreted, and displayed. Table 5-5 presents valuable lessons learned from real-world fractured rock characterization and remediation projects.

As a CSM nears completion, the guidance offers direction for developing remedial objectives and strategies. A table shows how to assess the different remedial strategies that may address mass stored in the compartments described in the 21-Compartment Model.

Strategies for monitoring contamination for compliance, system operation, and performance are also provided. The guidance explains how to design a monitoring well network that will provide the data needed to understand site conditions, remedy performance, and compliance.

When applied properly, mathematical models are powerful tools for understanding contaminant flow. Chapter 8 describes various model types, proper application, data needs, calibration, sensitivity, and limitations.

Finally, a discussion on stakeholderand regulatory considerations are presented, followed by a collection of case studies that demonstrate practical application of the concepts presented throughout the guidance.

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1 Introduction

Fractured rock sites can be intimidating, because remediating contaminated groundwater in fractured rock has not been widely conducted or studied. As a result, site managers often default to containing and monitoring contaminant plumes in fractured rock, rather than actively remediating the site to reduce risk. This approach has become problematic in areas of the United States where bedrock groundwater is a primary source of drinking and process water and demands on this groundwater are increasing. Recent advances in characterization and remediation for fractured rock sites, however, have made an active approach increasingly feasible.

Plume

The term "plume" does not precisely apply to contaminated groundwater in bedrock, but can be used if contaminant migration is understood in the context of fractured rock. For example, a plume may simply be a narrow area of contamination that is traveling within a transmissive fracture.

This guidance addresses these significant advances in skills, tools, and lessons-learned in understanding contaminant flow and transport in fractured rock environments. The physical characteristics of fractured rock influence the fate and transport of a broad range of contaminants. If the unique characteristics of fractured rock sites are understood, then modern tools and approaches can be applied to successfully set and meet characterization and remediation goals at these sites.

The geologic terrane offers insight into the evolution of the landscape, potential groundwater flow, boundary conditions, and contaminant transport at fractured rock sites. The difference between "terrane" and "terrain" is that terrane is a geologic area that differs from the surrounding material and is separated from this material by faults, while terrain is a single, distinctive rock formation. Lithologic, stratigraphic, tectonic, structural, and physiographic characteristics of the region are reflected in fracture patterns, surface features, and boundary conditions of the site. Each of these attributes influences fluid flow and contaminant transport. Additionally, fracture orientation, aperture, infilling, length, density, connectivity, planarity or waviness, and roughness play key roles in fluid movement.

Fracture flow, ranging from large regional chemical plumes that extend for many kilometers (and which may constitute acute environmental emergencies) to smaller local plumes, threatens to become bigger problems if left unaddressed. As a first step, fracture flow can be framed in one of three main scales:

- macroscopic (regional flow and flow across sites)
- mesoscopic (site scale flow)
- microscopic (flow in the rock matrix and between microfractures, typically investigated at the subcentimeter scale)

Scale tends to determine the tools used to characterize the flow of chemicals through fractures. A large-scale chemical plume in fractured rock is a problem not only at the macroscopic scale, but also at the mesoscopic and microscopic scales. Practicable large-scale remedies are often determined by understanding and mitigating smaller-scale fracture flow behaviors. By contrast, if fracture flow of contaminants is first recognized at the microscopic or mesoscopic scale, then it can be contained at that scale, thus preventing a regional problem.

While fluid dynamics heavily influences contaminant transport, which can vary with changing lithologies, the physical and chemical characteristics of the contaminant, compound, or mixture further define their transport and fate. The contaminants' inherent characteristics (solubility, density, vapor pressure, and K_{oc} among others) control their phase (solid, aqueous or gas) and thus subsequent transport. Because of these complexities, remediation in fractured rock requires a collaborative team of professionals in hydrogeology, stratigraphy, structural geology, geophysics, geochemistry, and various engineering disciplines. This team must investigate and interpret interrelationships of the regional geologic processes and site geologic characteristics, regional flow regimes affecting local fluid flow and contaminant transport, along with contaminant characteristics to define a conceptual site model (CSM) sufficient for making reliable decisions.

This guidance document dispels the belief that fractured rock sites are too complex to characterize and remediate. The physical, chemical, and contaminant transport concepts in fractured rock have similarities to unconsolidated porous media, yet there are important differences. These differences are the focus of this guidance. This guidance uses concepts and procedures described in *Integrated DNAPL Site Strategy* (ITRC 2011) and *Integrated Site Characterization* (ITRC 2015b) while noting how these strategies are adapted to the fractured rock environment.

This guidance first describes how the geologic history of a site, within defined physiographic provinces, can predict lithologies and the dominant tectonic forces that are reflected in local structures that control fluid flow (Chapter 2). Conceptualizing regional, local, and microscopic fluid flow further explains contaminant transport in the rock matrix and fractures or other openings (Chapter 3). Finally, a table summarizes a wide range of contaminants and properties that affect the fate and transport of contaminants in solid aqueous or gaseous phases (Chapter 4).

Once the geologic, hydraulic and chemical characteristics are understood, a fractured rock site can be characterized using a variety of tools. Chapter 5 provides an iterative process for characterizing the geologic, hydraulic, and chemical characteristics of a fractured rock site. This chapter also includes a searchable tools table containing over 100 tools and techniques, Finally, this guidance describes the importance and processes of managing data and interpreting results. These results are used to refine the CSM or, if necessary, dispute the initial CSM.

Although remediation technologies used at fractured rock sites are similar to those being used at unconsolidated porous media sites, their application requires special considerations in most fractured rock. Chapter 6 illustrates these differences through explanation, examples, and a case study. Monitoring strategies for fractured rock sites are described in Chapter 7 and models, applicable to fractured rock sites, are described in Chapter 8. Reference to these models are dispersed among the preceding chapters where they can be applied.

Case studies of successful fractured rock remediation are included to provide examples of how fractured rock sites can be evaluated and available tools applied to characterization and remediation.

1.1 Characterizing Fractured Rock

Traditional strategies used in unconsolidated porous media have often been inappropriately applied to fractured rock without success. This failed approach, in part, is due to a limited understanding of dual porosity and its effect on fluid flow and contaminant transport and storage. Dual porosity occurs when two distinct porosity regions are present: one in the rock matrix and one in the fractures of the rock. Even though most of the fluid flow may be within the secondary porosity (fracture porosity), much of the contaminant storage may be in the matrix porosity (primary porosity).

To successfully address contamination in fractured rock, sufficiently detailed conceptual site models (CSMs) must be developed. Although there is no universally accepted definition or description of a CSM, various governmental agencies, consulting firms and other organizations have developed their own definitions. The following resources offer a general explanation of CSMs in various contexts:

- *Effective Use of the Project Life Cycle Conceptual Site Model* (USEPA 2011)
- *Characterization, Modeling, Monitoring, and Remediation of Fractured Rock*

National Academy of Science (NAS 2015); see extensive discussion of “Hydrostructural Models” and “Microstructural Models”

- *Integrated DNAPL Site Characterization and Tools Selection* (ISC-1) (ITRC 2015b)
- *Integrated DNAPL Site Strategy* (IDSS-1) (ITRC 2011)
- *Conceptual Site Model Development* (Triad Resource Center)
- *Standard Guide for Developing Conceptual Site Models for Contaminated Sites, ASTM E1689-95(2014)* (ASTM 2014)

The CSM supports sound scientific, engineering, and policy-based decisions. Regardless of the project objectives or phase, a fractured rock CSM must be developed, documented, updated, and its assumptions refined, so that it can be used by project managers, scientists, engineers, regulators, public and tribal stakeholders, and site owners or managers.

1.2 Comparing Unconsolidated Porous Media CSMs and Fractured Rock

CSMs

To investigate contamination in fractured rock, the fundamental similarities, differences, and terminologies associated with both fractured rock and unconsolidated systems must be understood. Figure 1-1 illustrates key characteristics for both fractured rock and unconsolidated porous media within three broad disciplines: geology, hydrology, and chemistry. For each discipline, the figure illustrates fractured rock characteristics on the left of each column, and unconsolidated porous media on the right of each column. For example, as shown on the left geology column, the geologic framework of a site must be evaluated. In unconsolidated materials that framework depends on the depositional setting of the sedimentary environment, whereas in bedrock, the lithology and tectonic forces determine the physiography of the geologic terrane.

Figure 1-1 illustrates the investigative scale from macro (physiography or regional scale) at the top of the column to the micro (fabric or grain size) at the bottom of the column. The macro scale investigation informs the next steps in data collection in each of the disciplines. CSM development generally proceeds in each discipline according to the following steps:

Geology

- Consider regional rock types and local tectonic forces associated with the formation and fracturing of the bedrock. This information may be found in the published literature and is comparable to the evaluating the depositional environment of unconsolidated materials (such as fluvial, deltaic, marine, and glacial).
- Next, define the specific rock type. Are the rocks competent, weathered, or both, and what are the apparent rock structures and fabric? This analysis is comparable to considering unconsolidated porous media types (gravel, sand, clay) and their associated depositional environment (such as stratigraphy).
- After developing the overall fractured rock framework, determine the texture of the bedrock. This step is comparable to gathering information on of grain size distribution within unconsolidated materials.

Hydrology

- Determine the likely regional recharge/discharge boundaries before assessing the individual aquifers.
- Assess fracture patterns and orientation based on various lithologies in the region. This step is comparable to evaluating stratigraphic units in an unconsolidated system.
- Evaluate transmissive units within fractured rock aquifers including fracture orientation, aperture, connectivity, fracture density, planarity or waviness, and roughness. The transmissive units are controlled by lithology, tectonics/structure, and weathering (see Appendix A for karst settings and vesicular basalt).
- Review fractured rock primary porosity primary (rock matrix or micro fractures) and secondary porosity (fractures and partings of all types). This is a significant difference from unconsolidated porous media. With few exceptions (for example, fractured till), primary porosity dominates fluid flow in an unconsolidated porous media.
- Evaluate anisotropy of the system. Fracture flow takes place within a system of interconnected fractures, frequently with a small number of dominant flow and transport pathways. Groundwater flow in unconsolidated porous media is often treated as isotropic, although there can be discrete flow features that are controlled by lithostratigraphic layers and depositional history.
- Determine fluid flow in the fractured rock aquifer. Flow in fractured rock can be Darcian, non-Darcian and channel flow; whereas, flow in the unconsolidated sediments materials is interstitial and usually Darcian.
- Analyze potentiometric surface. Understanding the potentiometric surface and hydraulic gradients is important for both unconsolidated and bedrock aquifers. Anisotropy in bedrock aquifers may result in groundwater flow that is orthogonal to the potentiometric contours. Additionally, the apparent potentiometric elevation associated with a bedrock may reflect a weighted average of the hydraulic pressure and transmissivity of individual fractures intercepted by a single well. This condition may be similar to the potentiometric measurement associated with a well that spans multiple confined aquifers in unconsolidated strata.

Chemistry

Consider the following mechanisms, which do not necessarily depend upon one another:

- Dispersion in fractured rock aquifers can be one-dimensional (such as within a solution channel), two-dimensional (such as along a fracture plane or bedding), or three-dimensional (such as interstitial or equivalent porous medium). Dispersion in unconsolidated sediments materials is usually three-dimensional.
- Diffusive transport of compounds in fractured rock aquifers may occur in primary porosity of sedimentary rock and in matrix or secondary porosity in crystalline rock. In unconsolidated sediments, diffusion can be dominant

transport mechanism in low hydraulic conductivity deposits.

- Degradation of compounds in fractured rock aquifers can be chemically or biochemically controlled by the matrix and pore fluids and volatilization, similar to unconsolidated sediments.
- Entrainment (migration of solids / particulates) may occur via groundwater flow paths in large aperture fractured rock features. Entrainment is not typically associated with unconsolidated materials.
- Vertical emplacement of surface and near-surface contaminant releases may occur when the release is located near or above vertical bedrock fractures and structures (for example, down-dip migration to a location off-set from the release). Variations in primary porosity and stratigraphy in unconsolidated materials (for example, pore entry of NAPL in sand/accumulation of NAPL on a clay layer) control vertical emplacement in unconsolidated aquifers. Lithologic contacts in crystalline rocks and stratigraphy in fractured sedimentary rock may also influence fluid flow and contaminant transport. Contaminants emplaced in fractured rock may also end up in discontinuous (dead end) fractures.
- Contaminant sorption occurs in both fractured rock (sorption to microtextures and mineral surfaces) and unconsolidated sediments materials (sorption to organic carbon and grains).

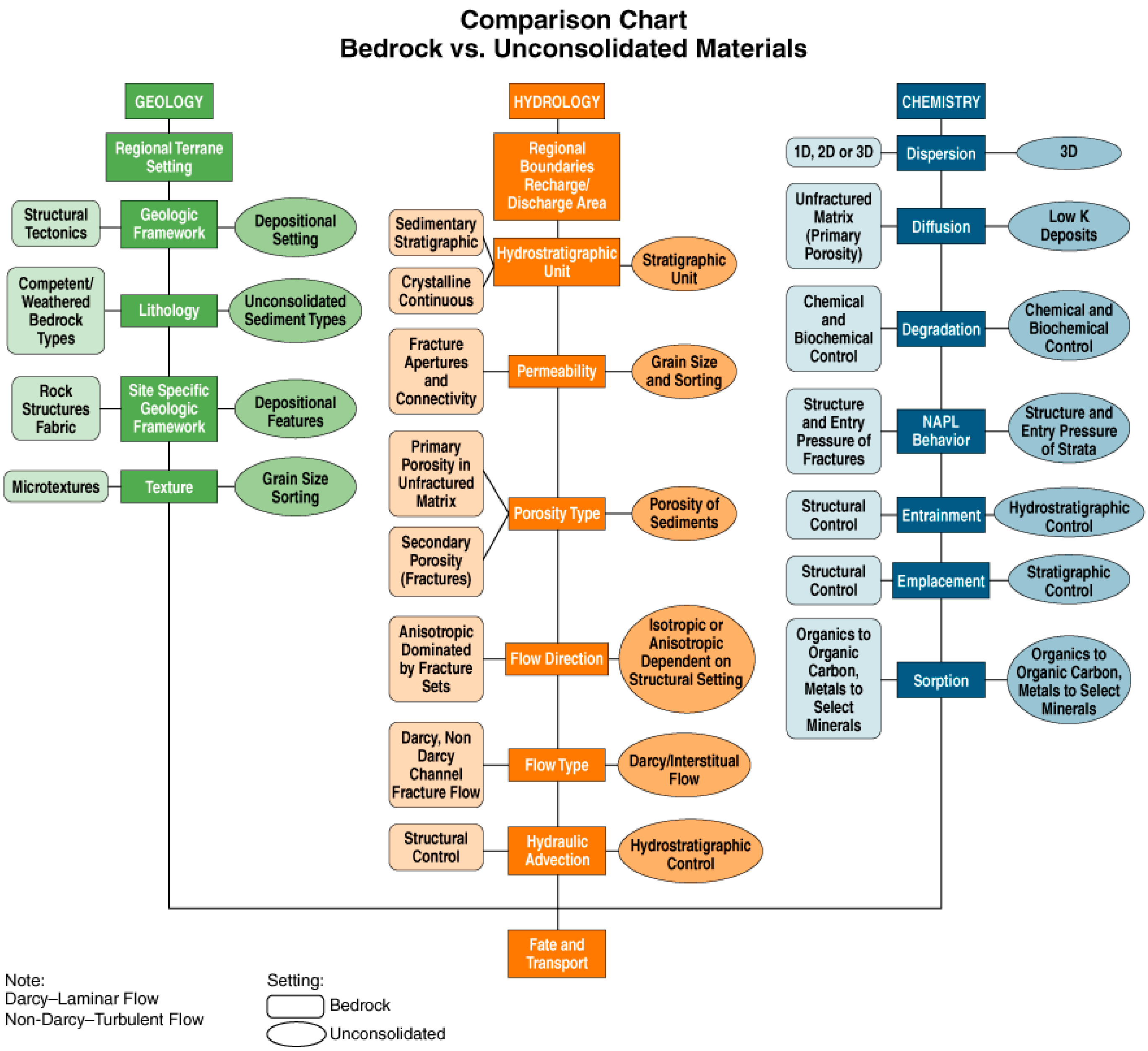


Figure 1-1. Bedrock versus unconsolidated rock types.

1.3 21- Compartment Model

The *Integrated DNAPL Source Strategy* (ITRC 2011) guidance document includes the 14-Compartment Model for application to unconsolidated media. This model is a valuable tool to illustrate and communicate where storage zones (or compartments) for contaminant mass are likely to be in an unconsolidated porous media flow system (for example, low permeability zones versus more transmissive zones). The model also illustrates the flux that is expected to occur between mass storage compartments (ITRC 2011).

For fractured rock environments, the 14-Compartment Model is expanded to a 21-Compartment Model to provide a similar method to illustrate and communicate likely mass storage, flow, and flux in fractured rock aquifers.

1.4 Value of Investigation

Collecting data from a fractured rock site requires efficiencies beyond what are often followed in unconsolidated media investigations. Applying the characterization practices and concepts to fractured rock sites outlined in this guidance will improve understanding of the site so that environmental professionals can select effective and cost-appropriate investigation and remedial methods. Reducing uncertainty fosters sound decision-making process for these sites. Thus, the money spent on a fractured rock site investigation can be considered as a return on investment. For a more detailed value analysis, see *Integrated DNAPL Site Characterization and Tool Selection* (ITRC 2015a), Section 1.3.

2 Geology

Knowledge of fractured rock geology, or "terrane," provides important context for investigating contaminated sites. Tectonic forces impart characteristic structures on rock formations that influence the evolution of the landscape, groundwater flow, and contaminant migration. For example, different rock types may be juxtaposed due to crustal deformations such as faulting, folding, and erosion. These deformations give rise to uplifting, unloading, and erosion, which generate tensional fractures and open bedding-plane fractures. Differential physical and chemical weathering, and eroding rock types that exhibit variable resistance to weathering, cause landforms and lineaments that may be evident on maps, aerial photography, and satellite imagery, reflecting the underlying bedrock structure. In some instances, these features may be buried and thus not evident on the surface. In many terranes, however, major faults and fractures can be inferred from topographic information alone. Anthropogenic characteristics of the terrane, such as mining activities, may also be resolved through terrane analysis.

Terrane or Terrain?

Terrane *is a block of the earth's crust that differs from the surrounding material and is separated from this material by faults (WikiDif 2017). In addition to being bounded by faults, terrane has a distinct stratigraphy, structure, and geologic history.*

Terrain, *on the other hand, is a single, distinctive rock formation or an area made up mostly of a particular rock or group of rocks (WikiDif 2017). While faults define terrane, faults may be absent from terrain.*

Analysis of the surficial and bedrock lithologic, stratigraphic, tectonic, structural, and physiographic characteristics allows the identifying of geologic patterns, features, and boundary conditions that influence fluid flow in fractured rock aquifers. Synthesis of this information provides a macroscale hydrogeologic framework. Taken together, the rock type and the geologic forces cause fracture systems and terrane fabric that influence groundwater flow patterns. This initial terrane analysis is refined during the characterization and design phases and the 21-compartment model assessment, which results in a more detailed and actionable CSM.

2.1 Elements of Terrane Analysis

A terrane analysis is an iterative process consistent with a CSM. Terrane analysis consist of six elements in the early stages of a fractured rock investigation:

1. Regional physical setting.
2. Bedrock lithology and stratigraphy.
3. Structural geology and tectonic setting.
4. Anisotropy and heterogeneity.
5. Hydrology.
6. Potential receptors.

A terrane analysis matrix is provided to help evaluate these elements and their interrelationships. This matrix can serve to organize the crucial elements of terrane analysis, which may be evaluated collectively or simultaneously, but not necessarily sequentially.

2.1.1 Potential receptors

The potential receptors within the geologic terrane provide the basis for more detailed investigation design. The initial geologic terrane assessment should identify potential receptors that may be exposed to contaminants. Potential pathways to receptors may include groundwater supply wells, surface water, migrating vapor/inhalation, direct contact, ephemeral drainage features, and surface discharge locations (such as seeps and wetlands).

2.1.2 Regional Physical Setting

The physical setting can be evaluated, from area- to regional-scale characteristics, through a desktop analysis and field reconnaissance. The terrane analysis is scale-dependent and is relative to the scale of the site investigated. Factors affecting the scale of the terrane analysis include, but are not limited to the following:

- size of the site and release
- length of identified lineaments
- proximity of potential receptors (such as surface water bodies or supply wells)
- mobility of chemicals of interest
- availability of exposed outcrops for direct inspection

The regional physical setting is determined by the physiographic province in which the site is located, and associated characteristics of the physiographic province. Physiographic provinces are characterized by their major rock types (igneous, sedimentary, metamorphic) structural attributes, topography, and drainage features (see lithology and fractured rock overview).

Visit the U.S. National Park Service regional geology discussion for illustrations and description of physiographic provinces in the U.S.

Within a specific physiographic province, physiography and topography may be evaluated using information and tools such as topographic maps, geologic maps, light detection and ranging imagery (LiDAR), and aerial photography, including stereoscopic analysis to investigate the terrane and its fabric (for example, ridges and valleys), which can show trends and surface expressions (Figure 2-1).

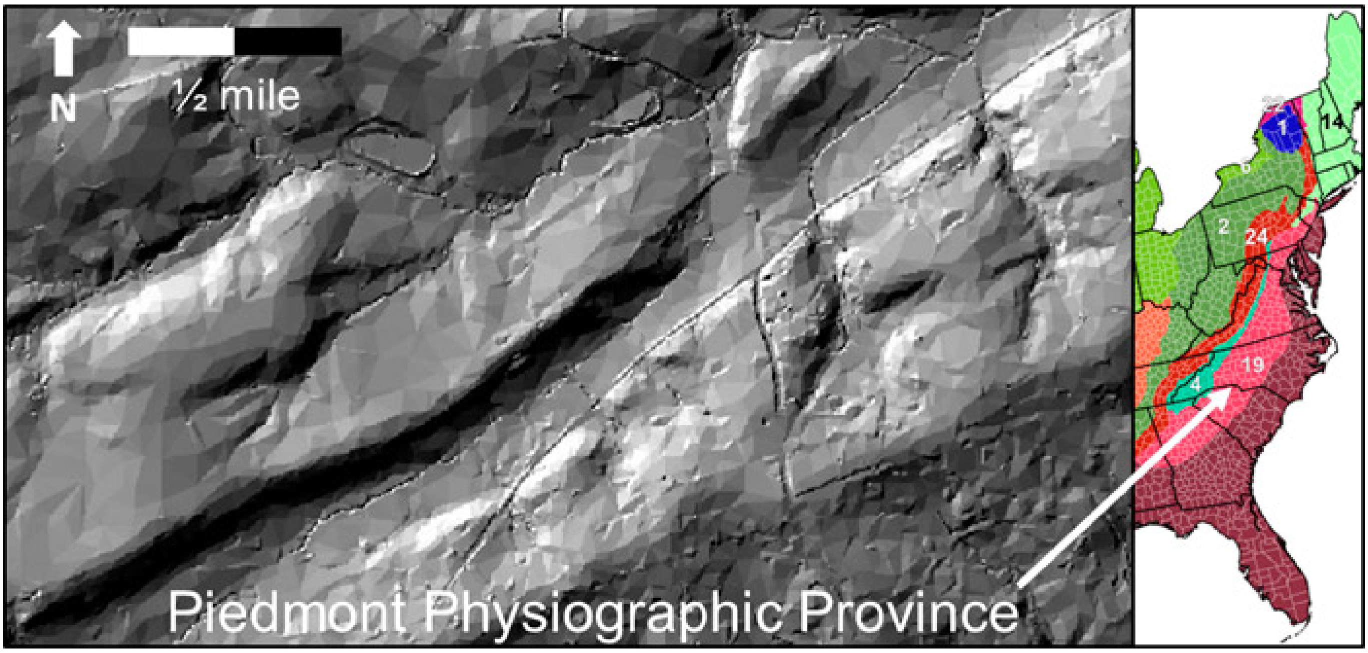


Figure 2-1. LiDAR image illustrating physiographic expression of metamorphic terrane including northeast-southwest trend in landscape.

2.1.3 Bedrock Lithology and Stratigraphy

Rock types and their specific lithologies and stratigraphy directly influence primary porosity (matrix), secondary porosity (fractures), fracture characteristics (orientation, aperture, infilling, length, planarity, roughness, connectivity, density, and the physiography), of an area or region. Determining the types of rock underlying a site and the surrounding area, therefore, is key to understanding fate and transport of contaminant. For instance, the lithology of underground mined ore bodies is invaluable information for characterizing a site. The position of ore zones is linked with underground mine workings or voids used to access the ore. As a result, the voids provide conduits for movement of water and air through barometric pumping, resulting in oxidation of the mineralized ore zones and generation of metal-laden and often acidic groundwater plumes.

This guidance provides a more detailed description of specific lithologies, including subcategories, mineralogy, porosity characteristics, associated drainage patterns, and hydrogeologic implications. USEPA's Contaminated Site Clean-Up Information webpage (CLU-IN) provides pictorial examples of various rock types, their physical descriptions, and hydrogeologic characteristics.

2.1.4 Structural Geology and Tectonic Setting

Compressional, extensional, decompression, and shear forces may result in several types of faults and features: normal, reverse (thrust) and strike slip, brecciated zones, foliation, inclined/folded sedimentary bedding, rift zones, or tabular intrusions. These distinct structural features influence fluid flow. These characteristics can be determined from evaluating desktop resources such as tectonic, geologic, and physiographic province maps, and supplemented by field reconnaissance. Structural characteristics commonly associated with rock types are summarized in the terrane analysis matrix.

Many tectonic structures are the result of either compression, extension, or shearing of the rock and tend to form parallel or at a predictable angle to the main stresses imposed on the rock, as shown in Figure 2-2. Tensional fractures are common in anticline, syncline, and isostatic rebound zones and should be considered as part of the site characterization, migration pathways, and drilling techniques (link Appendix C). Figure 2-2 illustrates the three primary types of faults (reverse, normal, and strike-slip) that form as a result of compression, extensional, and shear forces.

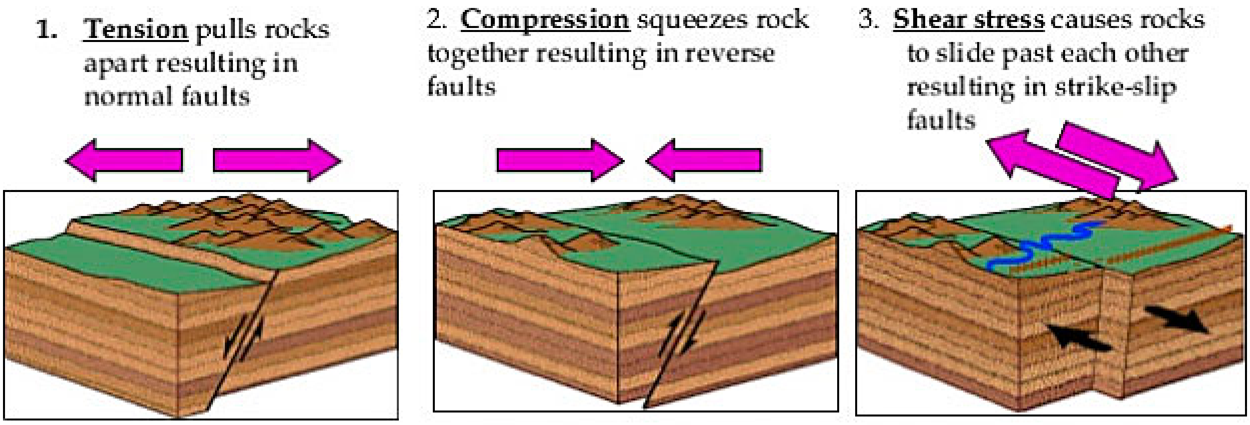


Figure 2-2. Reverse, normal, and strike slip faults due to compression, extensional, and shear forces.

Source: U.S. Geological Survey Department of Interior.

The following example illustrates how the structural geologic history of an area is used to predict type, orientation, distribution, and intensity of geologic discontinuities. The Triassic Basin in Virginia (Figure 2-3) was created by extensional tectonic forces. In this rift structure, gently dipping beds and extensive, subvertical fracturing can be expected. Investigation activities can then be designed to locate and verify these geologic discontinuities.

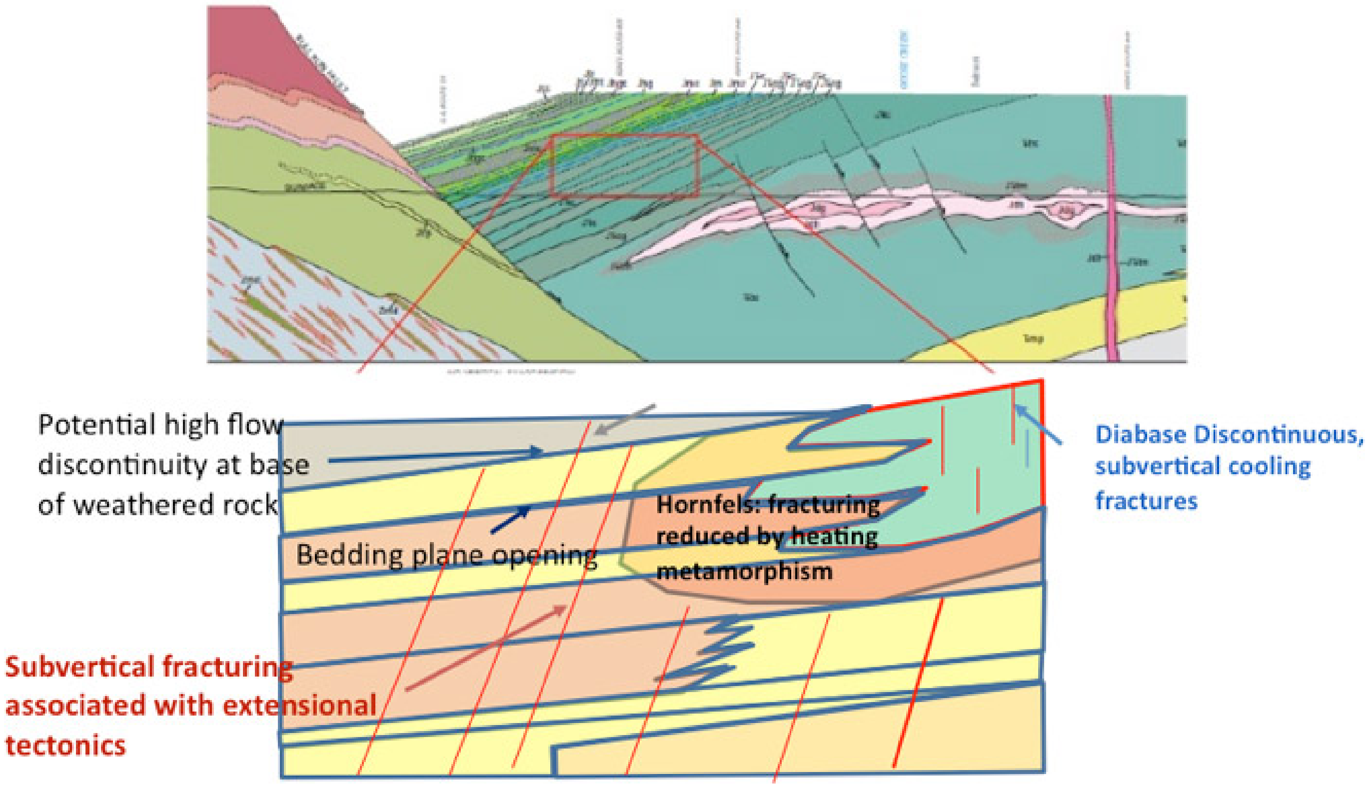


Figure 2-3. Tectonic and structural characteristics of the Triassic Basin in Virginia.

Compressional forces result in folding as illustrated in Figures 2-4 and 2-5. The folding of the rocks create a range of joints and other discontinuities whose orientations can be predicted if the geologic stress history is understood.

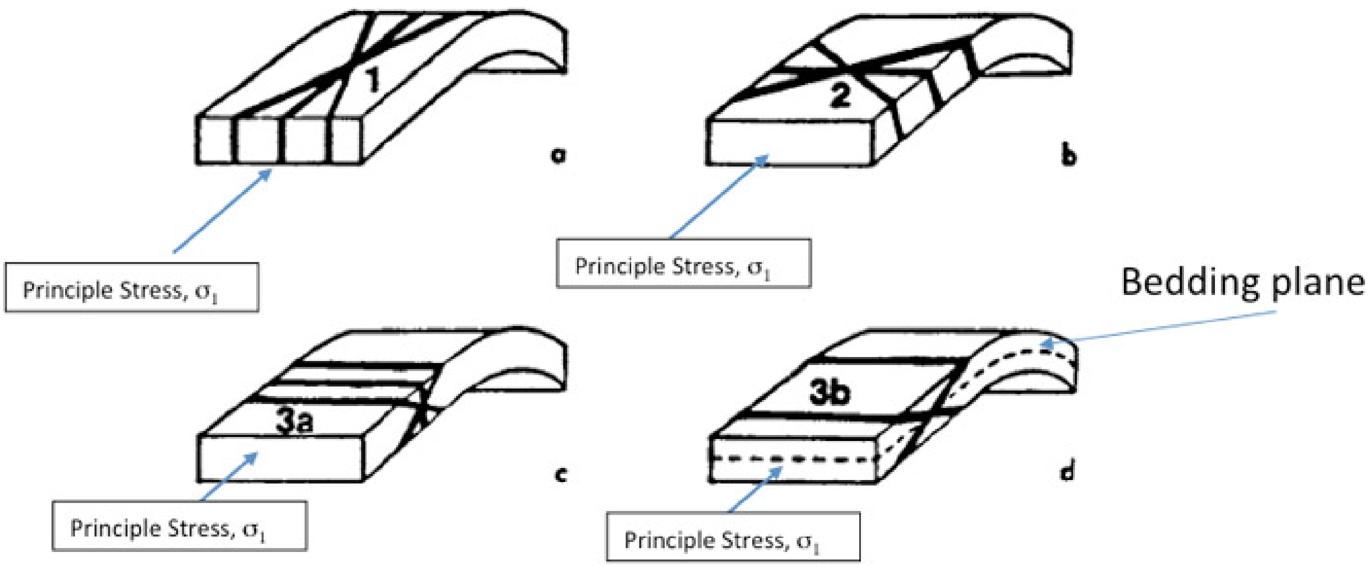


Figure 2-4. A generalization of dominant fold-related fracture or joint sets.

Source: (Stearns 1968)

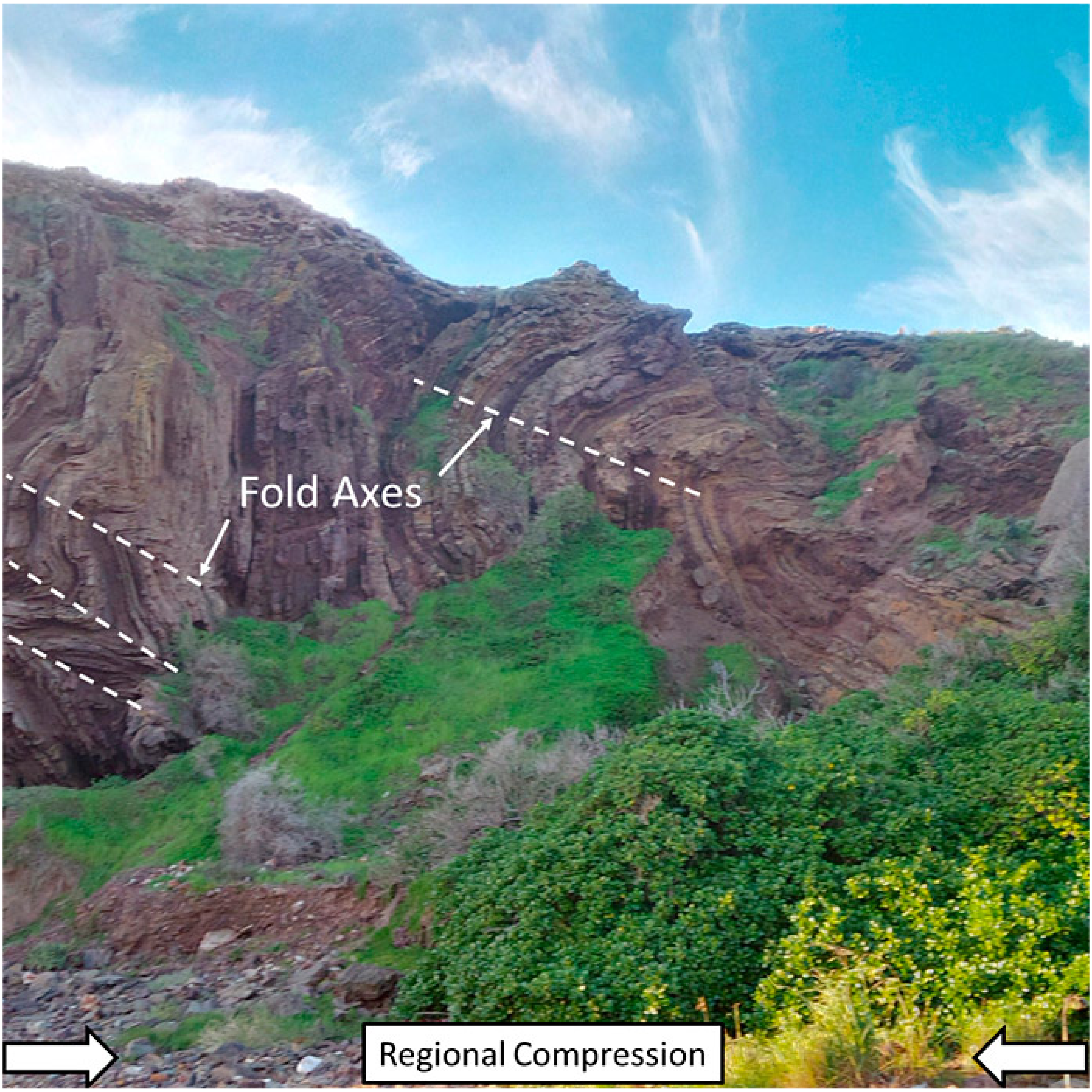


Figure 2-5 Intense folding of sedimentary rocks due to compressional forces with jointing along fold axis. Groundwater flow impeded left to right across page. Preferential groundwater flow along strike of folds into/out of page.

2.1.5 Heterogeneity and Anisotropy

Knowledge of the rock type and of the associated structure and tectonic history are combined to determine the expected degree and geometry of anisotropy and heterogeneity that may occur within the terrane. Heterogeneity in fractured rock is the condition where, for a given property (usually hydraulic conductivity), there is a spatial variability and the rock properties are different at various locations. This condition is in contrast to homogeneity, which refers to the condition in which one or more properties are the same at all locations. Anisotropy should be considered when assessing groundwater fracture flow direction due to structural or stratigraphic orientation. Intrusive (Link Appendix C) investigations may be guided by the suspected preferential flow direction due to anisotropy.

The terrane analysis matrix indicates the degree of anisotropy and potential for heterogeneity within aquifers consisting of a variety of rock types and subjected to differing degrees of structural/tectonic deformation, dissolution processes, intrusive/extrusive processes, and thermal history. Figure 2-6 illustrates the characteristics and differences of isotropy, anisotropy, homogeneity, and heterogeneity.

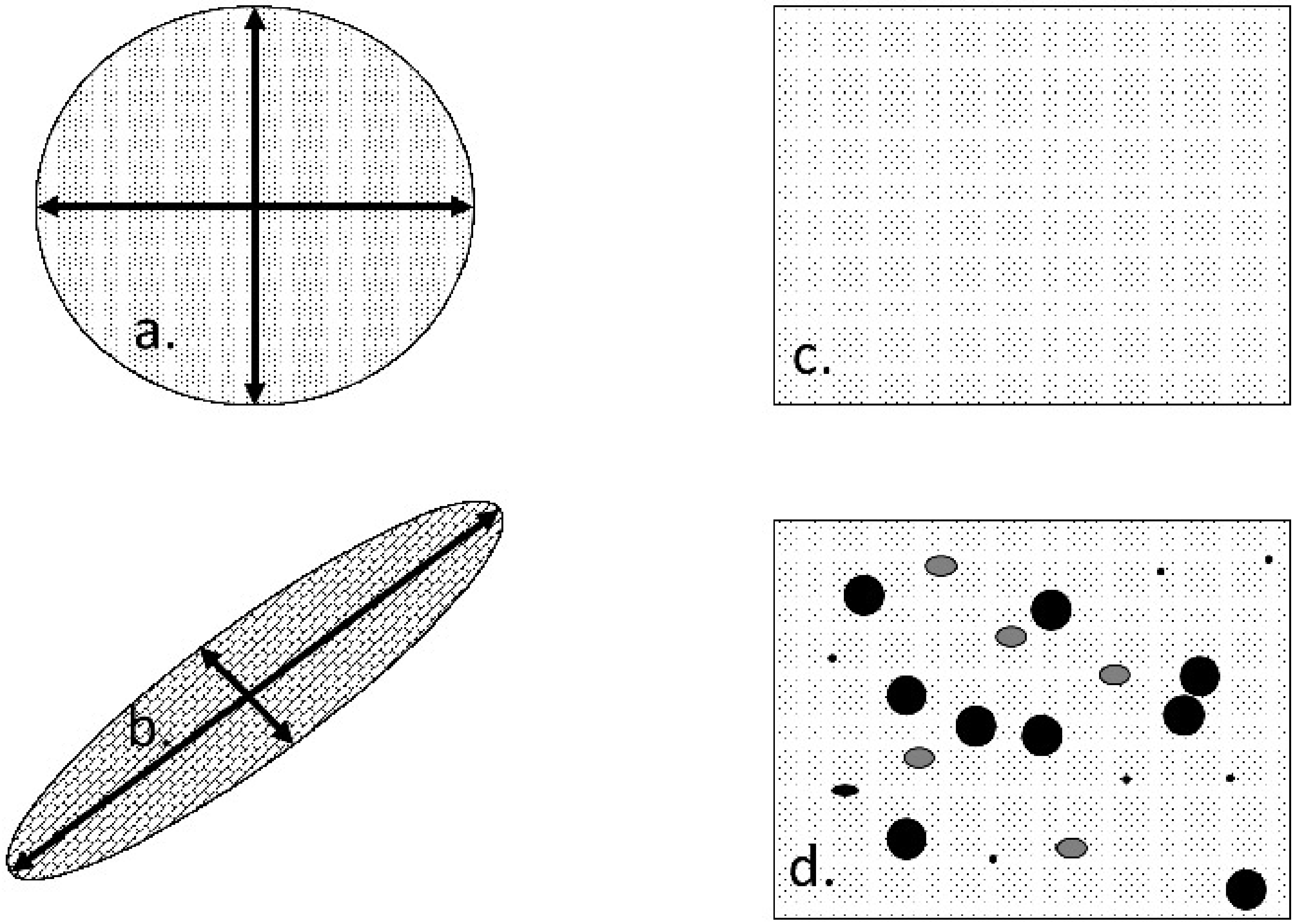


Figure 2-6. Hydraulic conductivity (K) in an aquifer: a) Isotropy – K is the same in all locations. b) Anisotropy – K is significantly greater in the NE/SW directions. c) Homogeneity – K is the same at all locations (top right). d) Heterogeneity – K is different at different locations.

2.1.6 Hydrology

Surface water features (such as creeks, streams, rivers, lakes, seas, and oceans) represent hydraulic boundary conditions (discharge or recharge boundaries, for example) that influence groundwater flow directions and hydraulic gradients within the physical framework consisting of the lithology, structure, and topography. Surface water features often reflect the geologic terrane, fabric, and underlying structural geology. In some cases, however, local recharge to surface water may occur but regionally may flow beyond the local boundary. Appendix B Table B-1, illustrates types of drainage patterns (surface hydrology) that occur with various terranes and underlying rock types and structures. Figure 2-7 illustrates an example of the superposition of a surface water drainage within the geologic terrane, which has developed preferentially along the strike of schist foliation. General hydrology information can be obtained from USGS topographic maps. More detailed hydrology is often necessary for the specific site, which can be obtained with LiDAR data, aerial photographic imagery, field reconnaissance (for example, ground truthing) or GPS data, and then developing hydrology line work using ArcGIS or similar programs combined with GIS software.

Figure 2-7. Stream valley eroded into tilted layers of rock (schist).

2.2 Benefits of Terrane Information for the Initial CSM

Terrane analysis is used to develop an initial terrane-based CSM framework. As part of this effort, it is important to consider the following: relative geometry of hydraulic boundaries, hydraulic gradient, rock fabric orientation, degree of weathering and contaminant sources and receptors, including where groundwater saturation occurs relative to the physical setting and the overburden/ bedrock interface. Figure 2-8 shows initial terrain CSM examples that illustrate the potential relative influences of the six elements.

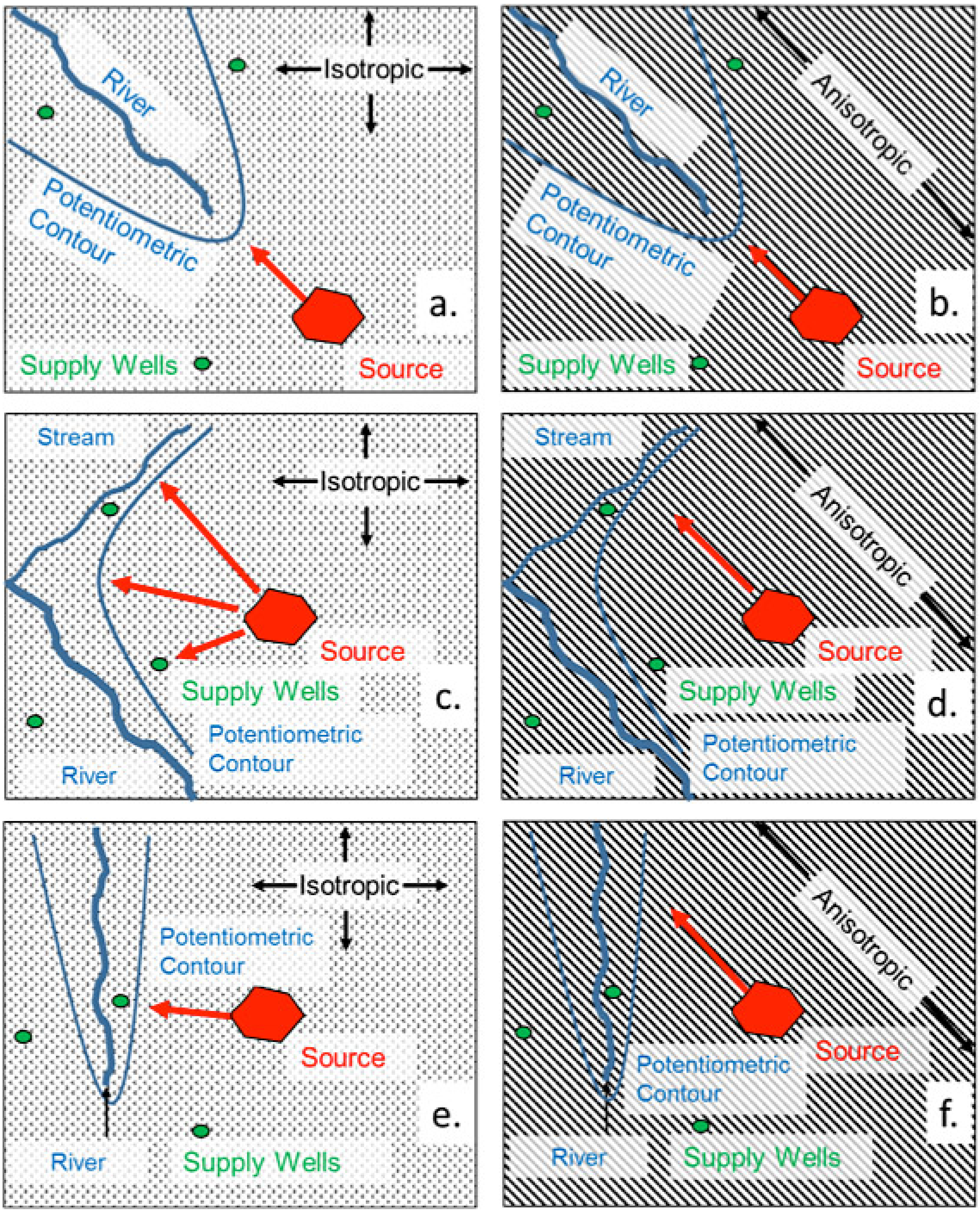


Figure 2-8. Initial CSM examples of contaminant source, flow direction, hydraulic boundaries, and receptors. Red arrows indicate flow direction but not magnitude of velocity or hydraulic gradient. a) Isotropic flow orthogonal to hydraulic gradient, no supply wells affected. b) Anisotropic flow orthogonal to hydraulic gradient, no supply wells affected. c) Radial isotropic flow orthogonal to hydraulic gradient, supply wells potentially affected. d) Linear anisotropic flow to a tributary stream, supply well potentially affected. e) Isotropic flow orthogonal to hydraulic gradient, supply well potentially affected. f) Anisotropic flow, oblique to hydraulic gradient, supply well not affected.

2.3 Terrane Analysis Case Study

Without a terrane analysis, potential receptors can be missed. In addition, the bedrock geochemistry should be considered for its potential effect on contaminant migration. A terrane analysis case study that was verified and validated through high density intrusive characterization is presented in Figure 2-9. This example highlights each element of the terrane analysis matrix.

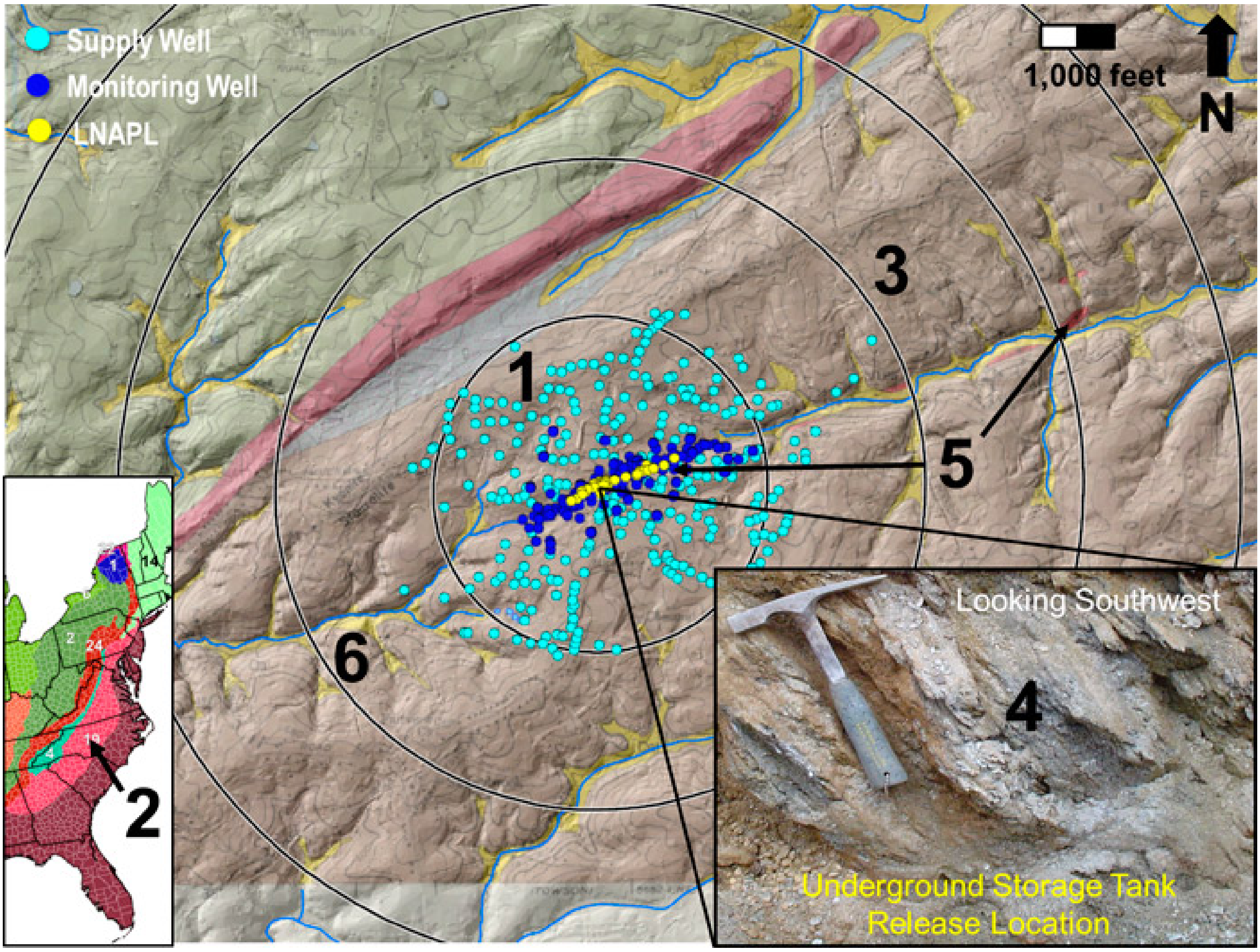


Figure 2-9. Case study demonstrating terrane-influenced migration of LNAPL within foliated, metamorphic rock and trellis drainage system surrounded by groundwater supply wells. Elements of terrane analysis matrix are denoted by number: 1) potential receptors, 2) physiographic province, 3) lithology, 4) structure, 5) anisotropy / heterogeneity, 6) hydrology. Concentric circles represent radii from release in ½ mile increments.

The elements of the terrane analysis case study are described in terms of the six components of the terrane analysis matrix:

1. **Potential Human and Ecological Receptors.** Potential receptors include private supply wells installed into bedrock and streams incised into bedrock that are hydraulically connected to groundwater. Contaminant vapors could migrate through bedrock fractures and present vapor intrusion issues.
2. **Regional Physical Setting.** The site is located within the Piedmont Physiographic Province. The map of physiographic provinces (Figure 2-1) shows that the Piedmont has a northeast-southwest structural trend. According to the USGS (Swain 2004):

   > *"The Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces are underlain by metamorphic, igneous, and sedimentary rocks; gneiss, schist, granite, and siliciclastic sedimentary rock underlie almost two-thirds of the study area* **[Lithology]***. Following faulting and folding, as well as one or more periods of metamorphism and igneous intrusion* **[Structural Geology and Tectonics]** *of the rocks in most of the study area, the entire area was* ***uplifted*** *during the Cenozoic Era. Subsequent* ***weathering and erosion*** *enlarged existing fractures in the bedrock and may have created new fractures by stress relief."*

   The aquifers of the Piedmont Physiographic Province are a major source of drinking water supplies in the Eastern United States, with documented transmissivity values for terranes in the Piedmont range from 9 to 1,400 ft^2/d (Swain 2004).
3. **Lithology.** The lithology of the case study area consists of the metamorphic rocks gneiss, quartzite, marble, and

schist. The site itself is specifically located within schist (crystalline, metamorphic rock exhibiting foliation).

4. **Structure.** The foliation of the schist is the predominant structural characteristics, which strikes northeast and dips northwest, imparting a regional fabric to the terrane.
5. **Anisotropy and Heterogeneity.** The structural orientation of the schist results in anisotropy that strongly influences the direction of groundwater flow and contaminant migration (northeast and southwest) along foliation strike. The local occurrence of gneiss within the schist provides an element of heterogeneity.
6. **Hydrology.** The characteristic trellis drainage pattern associated with foliated metamorphic terrane is evident in Figure 2-10. These streams provide hydraulic influence on groundwater flow as discharge boundaries (potential surface water receptors with fixed head conditions). The physiography is influenced by differential weathering and erosion, which has resulted in more resistant ridges and less resistant valleys where streams occur.

2.4 Terrane Analysis Summary

The example terrane analysis illustrates that foliation of the bedrock, which is expressed as regional terrane fabric (northeast-southwest trending ridges, valleys, geologic contacts, and streams) influenced the direction of contaminant migration to be linear to the northeast and southwest. The hydraulic gradient for groundwater flow in this terrane is toward the headwaters of streams that are also aligned northeast-southwest according to the foliation and regional terrane fabric. Many potential supply-well receptors exist in the area, but few are affected due to the terrane influence on contaminant migration and groundwater flow.

The terrane analysis provides an initial hydrogeologic framework (initial CSM), which, when incorporated into the CSM, can be used to guide and direct subsequent site investigation, remediation, and risk management measures. Subsequent work is necessary to understand and validate site-specific characteristics of fracture flow, further development of a sufficiently detailed and actionable CSM, and the assessment using the 21-compartment model.

3 Hydrology: Fluid Flow

This section examines fluid flow at three physical/investigation scales that are relevant for fractured rock:

- macroscopic (regional flow and flow across sites)
- mesoscopic (flow at a site scale)
- microscopic (flow in the rock matrix and between microfractures, typically investigated at the sub-centimeter scale)

At each of these scales, nine key characteristics influence fluid flow in fractured rock. Although these characteristics are generally present at all scales, the focus of this discussion are those characteristics most relevant to fracture flow at each individual scale. Most of these characteristics are not as relevant to unconsolidated porous media, and recognizing the differences between the two systems is critical to designing an effective remedial strategy in fractured rock**.**

Understanding fluid mechanics is key to characterizing fractured rock sites, with special consideration of the vapor phase and its differences compared to fluid flow in fractures. For purposes of this guidance, any type of fluid flow (such as NAPL or DNAPL) is considered similarly as "fluid." See Section 4 for additional information on contaminant transport as it pertains to fluid flow in fractured rock.

There are inherent limits to observing and evaluating the nine characteristics and their influence on flow. The physical scale of a particular feature or mechanism largely determines how it influences a particular remediation problem. See Case Studies for specific applications using the tools and techniques to characterize and remediate fractured rock sites. In comparison to sites underlain by unconsolidated sediments, fractured rock sites often require additional evaluation to understand the characteristics influencing fluid flow.

3.1 Fractured Rock Characteristics

The characteristics intrinsic to fractured rock that influence fluid flow, direction, and storage include:

- matrix lithology
- orientation
- aperture
- infilling
- length
- density
- connectivity
- planarity or waviness
- roughness

Figure 3-1 presents a range of fracture characteristics, hydraulic properties, and flow and transport mechanisms that are addressed directly or indirectly by scale (microscopic, mesoscopic, and macroscopic). See Section 5.4 and Section 5.5 for discussions on establishing data collection objectives, designing data collection process, and selecting investigation tools to characterize these properties.

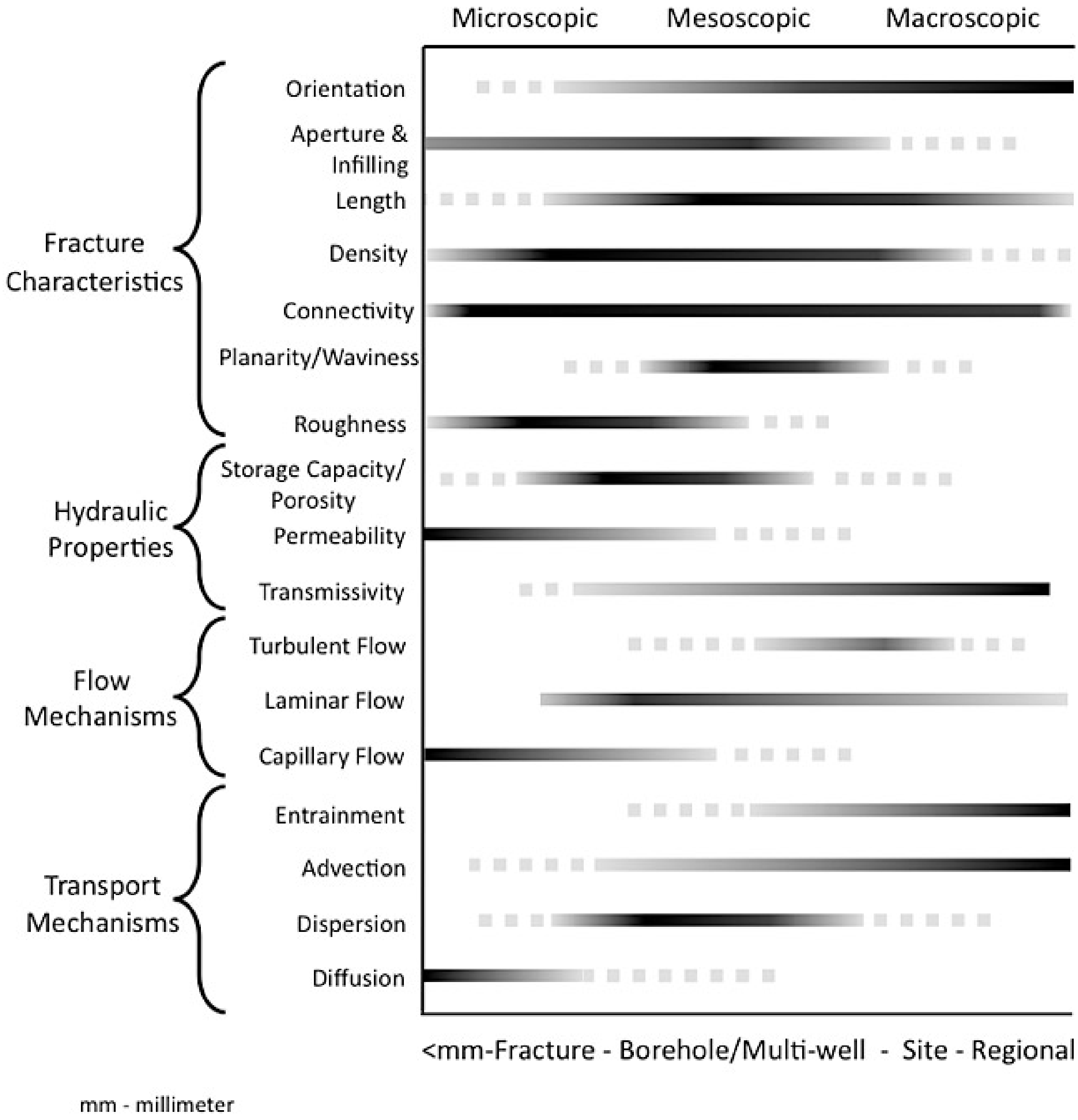


Figure 3-1. Range of fracture characteristics, hydraulic properties, and flow and transport mechanisms.

While these characteristics are always present to some degree in fractured rock (Figure 3-2), their relative importance for fluid flow varies depending on the observational scale of interest. Certain characteristics may be negligible with regards to fluid flow, depending on the scale.

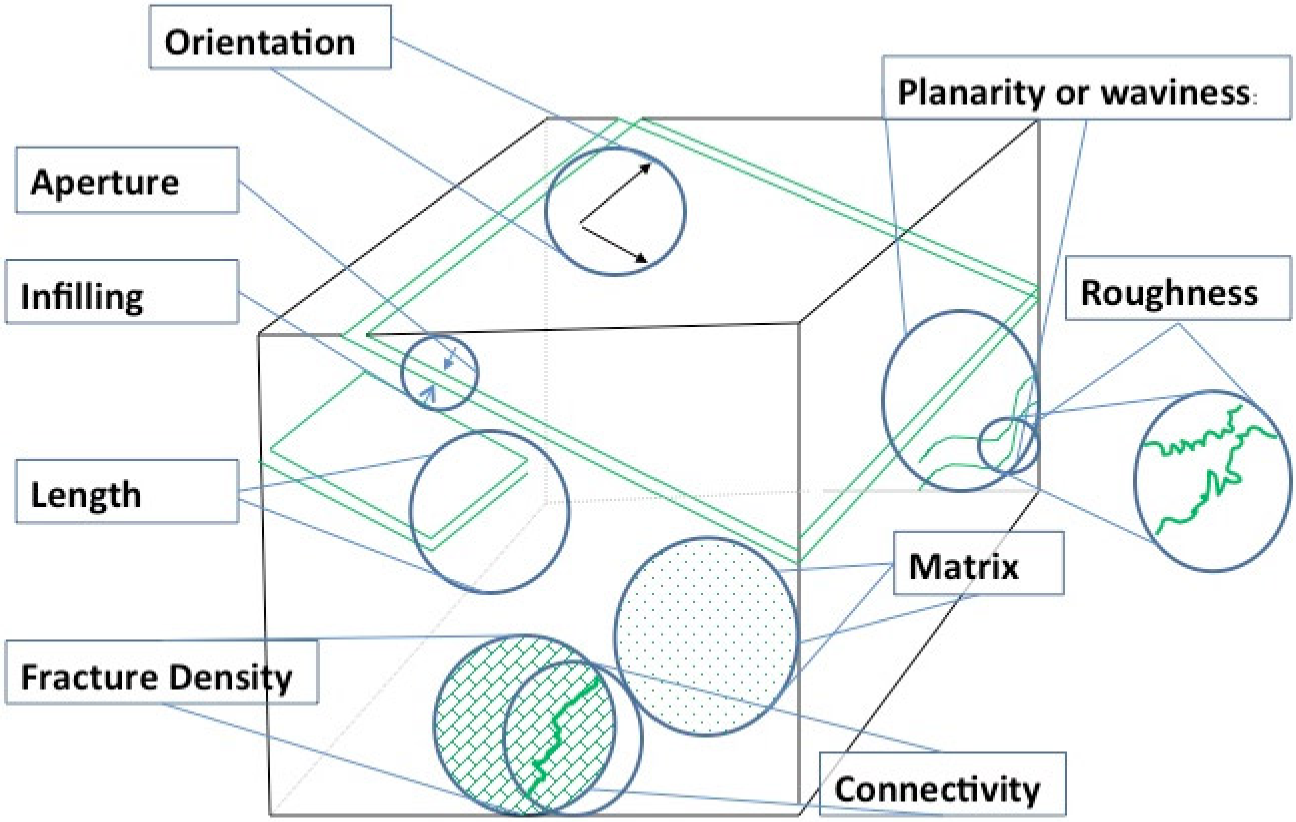


Figure 3-2. Fracture characteristics.

3.1.1 Matrix Lithology

Rock matrix type or character refers to the lithology (from a mineralogical and petrological perspective), grain or crystal size distribution and fabric, primary porosity (void spaces, which can include microfractures), inorganic and organic cementation/binding materials and their stability, bedding planes, paleochannels, sedimentary sequences with variable grain size, grain imbrication, lineations, nonconformities, and overall connectivity within the primary porosity network. Depending on the lithologic sequence, typical planar features can also be applicable to planar fractures. These combined matrix properties control the storage of contaminants in rock, connected fractures, and flow through the matrix.

The key features that influence storage and flow potential in fractured rock are matrix porosity (primary porosity), matrix intrinsic permeability, and the properties of the fluid of interest, respectively. Typical ranges for total porosity of common rock types are presented in Table 3-1. These ranges include the matrix porosity and fractures (secondary porosity). Matrix porosity is not always higher than fracture porosity for given fractured rock. In general, fracture porosity typically determines overall contaminant flow potential.

Table 3-1. Porosities for common rock types

Rock Type	Total Porosity (%) (Matrix and Fractures)
Claystone/Mudstone	21-45[1]
Shale	0-10[1,2]
Siltstone	21-45[1]
Fine grained sandstone	14-49[1]
Medium grained sandstone	30-44[1]
Limestone/Dolomite	0-40[2]
Karst Limestone	0-50[2]

Rock Type	Total Porosity (%) (Matrix and Fractures)
Tuff	7-55[1]
Basalt	3-50[1,2]
Gabbro (weathered)	42-45[1]
Granite (weathered)	34-57[1]
Fractured Crystalline Rock	0-10[2]
Dense Crystalline Rock	0-5[2]
Schist	4-49[1]
[1](Morris 1967) [2](Davis 1966a)	

3.1.2 Fracture Orientation

Fracture orientation is the position of a fracture in three-dimensional space, typically defined by the *strike* of the fracture (the compass direction of a horizontal line on the fracture plane face), and its *dip* (or maximum slope angle of the fracture plane angle measured off the horizontal perpendicular to the strike). Fracture orientation of multiple fractures making up particular fracture sets is often represented using stereographic projections. Fracture orientation generally constrains the potential directions in which fluids can flow in a fractured rock system. Above the water table or vadose zone, aqueous fluid flow generally runs down the face of the structural feature (down dip). In the saturated zone, aqueous fluid flows along the face of the structure or fracture (along strike), although the degree to which it does so depends on both the dip angle and the gradient direction at and below the water table. Vapor phase above the water table may flow freely along a fracture plane; however, fracture orientation generally influences the potential directions that fluids can flow in a fractured rock system.

Stereographic Projection

The stereographic projection is used in structural geology and engineering to analyze the orientation of lines and planes with respect to each other. The stereonet is a type of standardized mapping system that represents various angles in 3D space on a 1D paper.” (Wiki 2013)

The block diagrams in Figure 3-3 illustrate how strike and dip control flow of aqueous and nonaqueous phase liquids in a fracture and how different apparent plume patterns emerge depending on boreholes, wells, and depth. Figure 3-3a Vertical Structure, Figure 3-3b Steeply Dipping Structure and 3-3c Simple Shallow Dipping Structure.

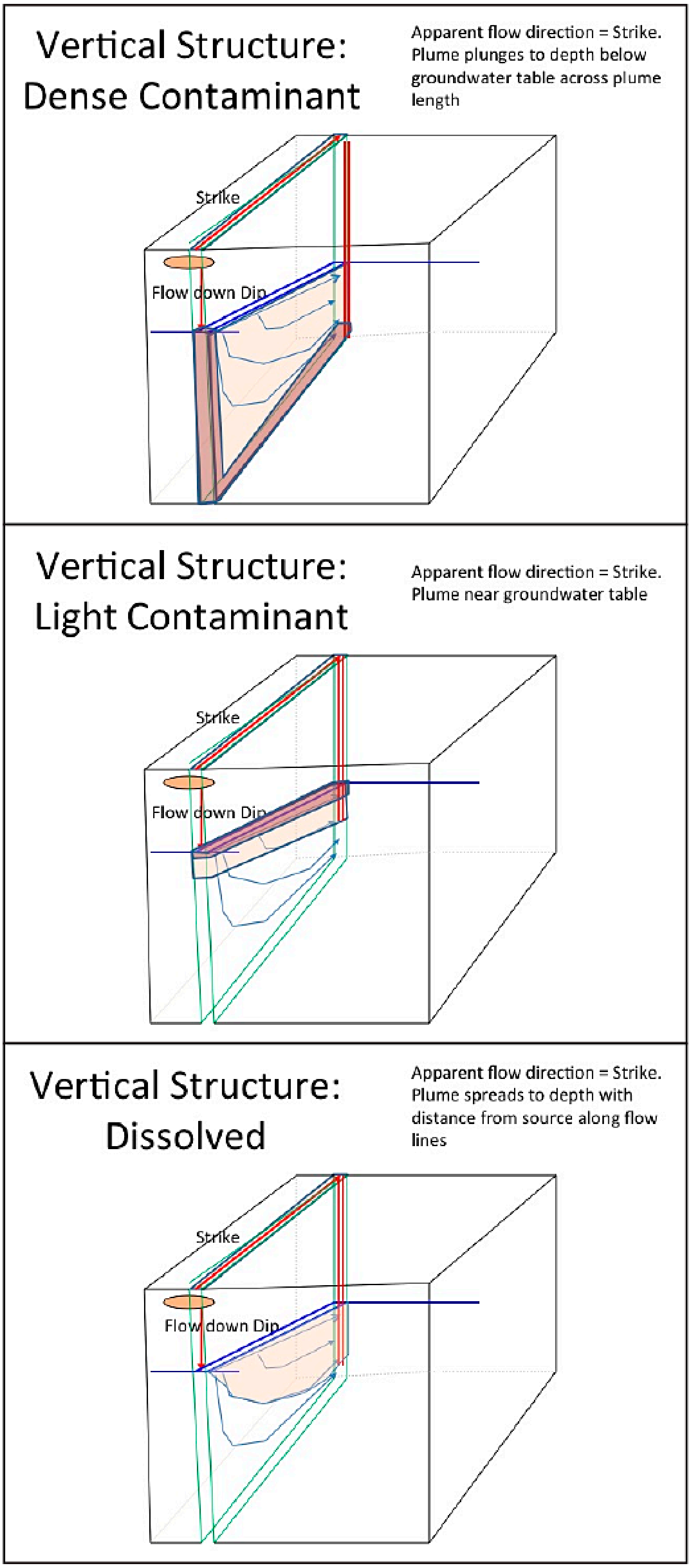

Vertical Structure:
Dense Contaminant
Apparent flow direction = Strike.
Plume plunges to depth below groundwater table across plume length
Strike
Flow down Dip
Vertical Structure:
Light Contaminant
Apparent flow direction = Strike.
Plume near groundwater table
Strike
Flow down Dip
Vertical Structure:
Dissolved
Apparent flow direction = Strike.
Plume spreads to depth with distance from source along flow lines
Strike
Flow down Dip

Figure 3-3a

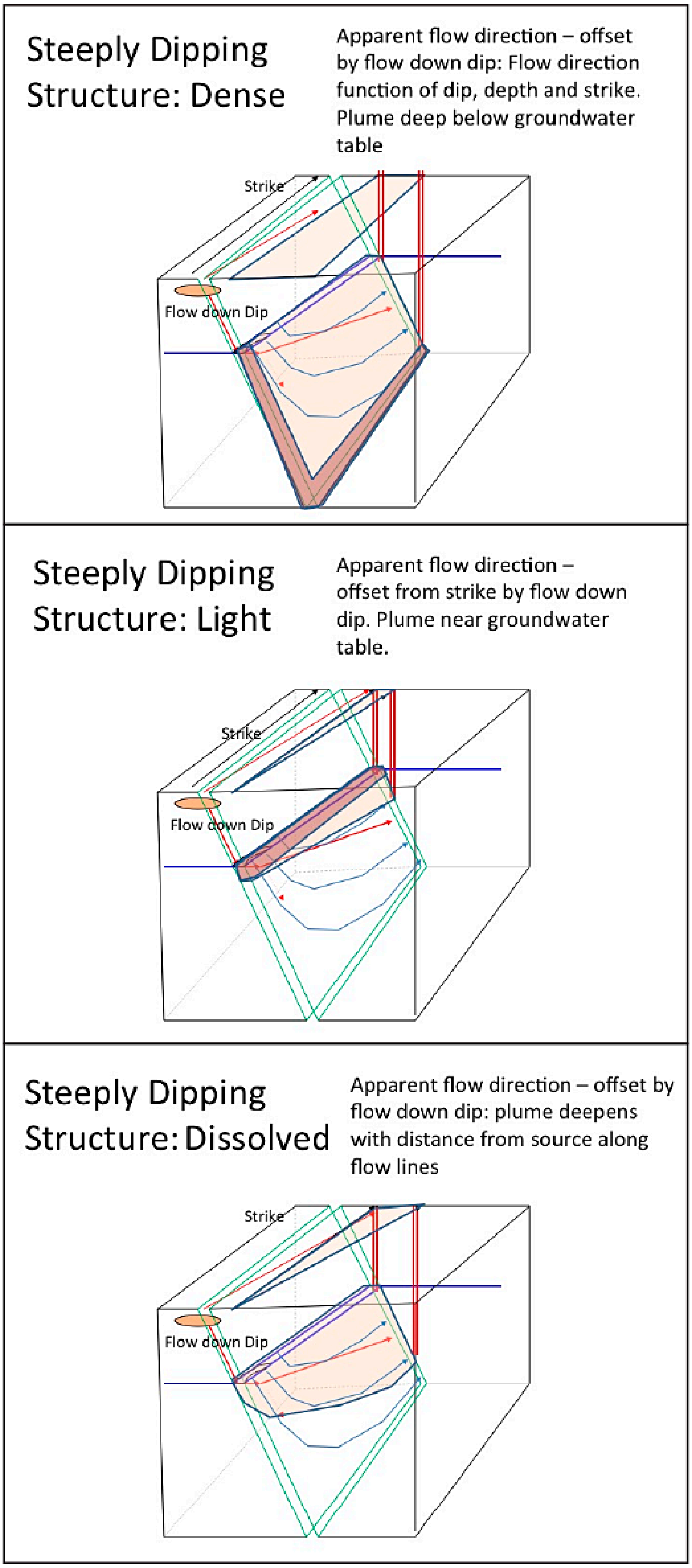

Steeply Dipping Structure: Dense
Apparent flow direction – offset by flow down dip: Flow direction function of dip, depth and strike. Plume deep below groundwater table
Strike
Flow down Dip
Steeply Dipping Structure: Light
Apparent flow direction – offset from strike by flow down dip. Plume near groundwater table.
Strike
Flow down Dip
Steeply Dipping Structure: Dissolved
Apparent flow direction – offset by flow down dip: plume deepens with distance from source along flow lines
Strike
Flow down Dip

Figure 3-3b

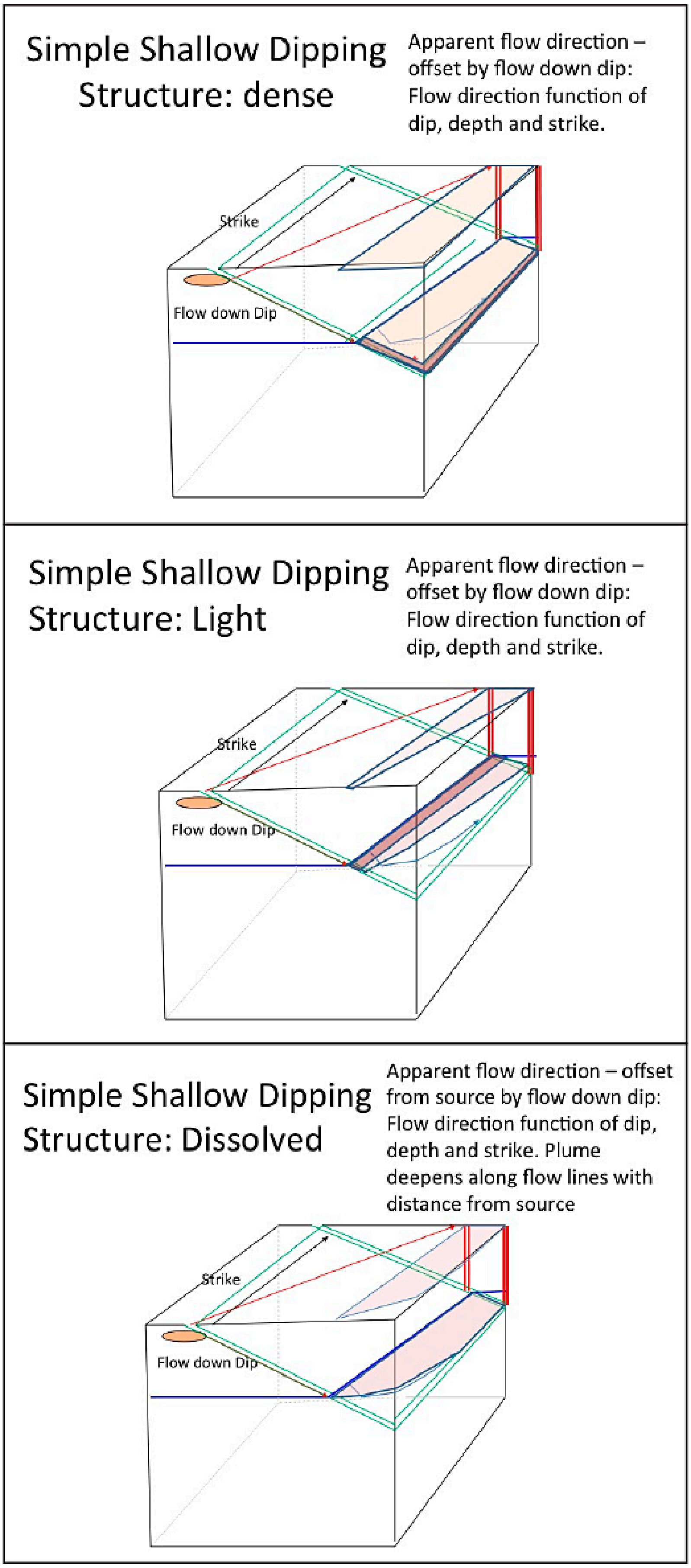


Figure 3-3c

Figure 3-3. Block diagrams illustrating strike and dip and influence on flow in a borehole or well located within fractured rock: a) vertical fractures b) steeply dipping c) simple shallow dipping).

Anisotropic rock systems vary with respect to groundwater and dissolved-phase aqueous flow in a rock formation. For example, dipping fractures exert differing degrees of anisotropy. A continuum of anisotropy exists ranging from the vertical fractures (maximum anisotropy) to horizontal fractures, which impart no anisotropy. Many intermediate anisotropies exist between these two extremes. It is important to collect hydraulic parameters, such as hydraulic gradient and conductivity, in multiple dimensions to evaluate the degree of anisotropy in a fractured rock system. Alternatively, if anisotropy of the fractured rock system is well understood, these variations in hydraulic gradient and conductivity parameters may be effectively estimated based on single dimension measurements or empirical estimates.

Figure 3-4 presents three examples of the continuum of anisotropy that can occur in fractured rock. Example A represents a strongly anisotropic fractured rock system, which is vertically fractured. In this example, the groundwater flow direction is largely determined by the strike of the fracture, but the prevailing hydraulic gradient also plays a part. If the fracture strike is north-south, then the groundwater is constrained to flow either north or south, depending on the direction of the prevailing hydraulic gradient. As the dip angle lessens, an inclined fracture is produced (Example B) and variable flow directions become possible, depending on both the prevailing gradient direction and the fracture strike orientation. Example C illustrates a horizontal fracture imparting no anisotropy; the system is isotropic and the flow is controlled entirely by the gradient direction. A gently dipping fracture would also be similar, but not identical, to Example C. This fracture would act much like Example C, even though it has a defined strike; a multitude of flow directions would be possible, with the actual direction being largely determined by the gradient.

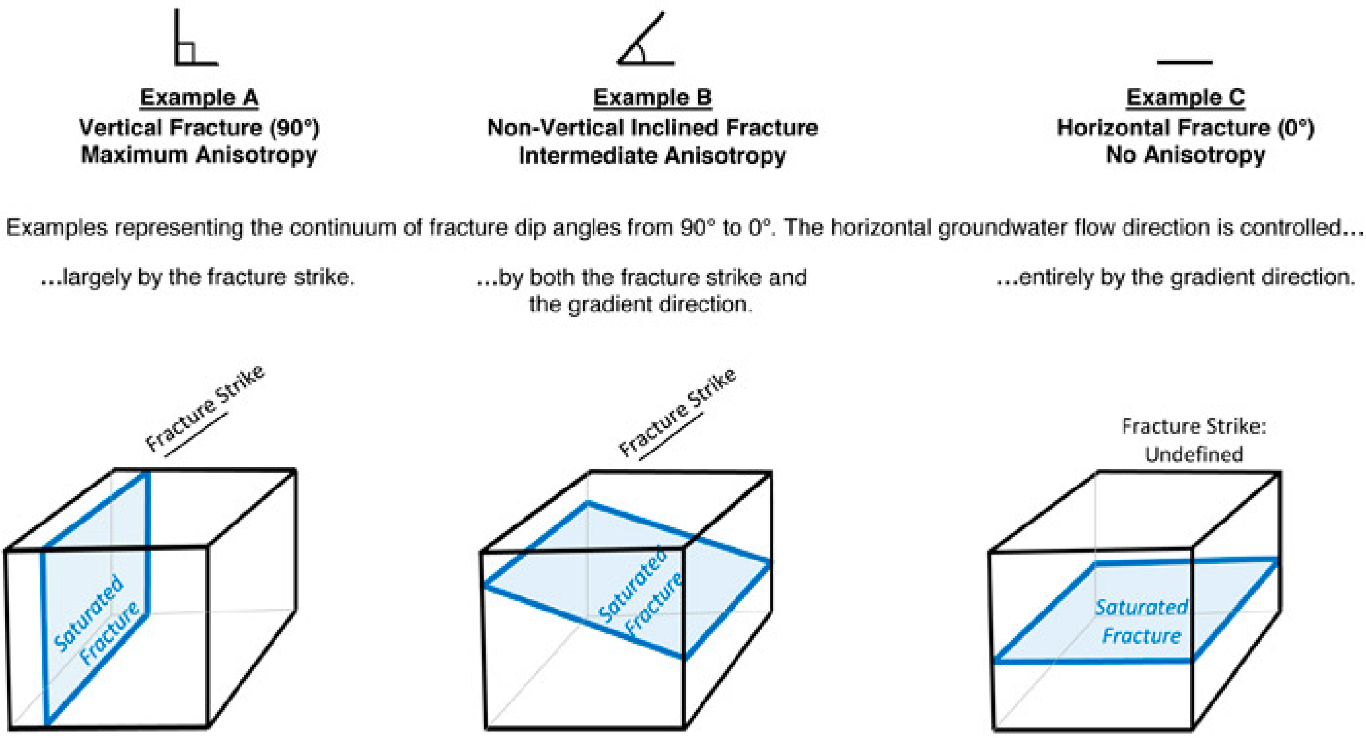


Figure 3-4. Influence of fracture dip angle on flow and anisotropy.

3.1.3 Fracture Aperture and Infilling

Fracture aperture is the width of the unfilled fracture opening. The fracture aperture can vary over time and space due to changes in in situ stress fields or dissolution and precipitation caused by rock weathering and biogeochemical processes. The larger the cross-sectional area of a fracture (width times height), the greater the flow capacity. For an idealized parallel-sided fracture under laminar flow conditions, a general cubic power law relationship exists under laminar flow conditions (Snow 1969), where a ten-fold increase in fracture cross-sectional area results in a thousand-fold increase in flow capacity.

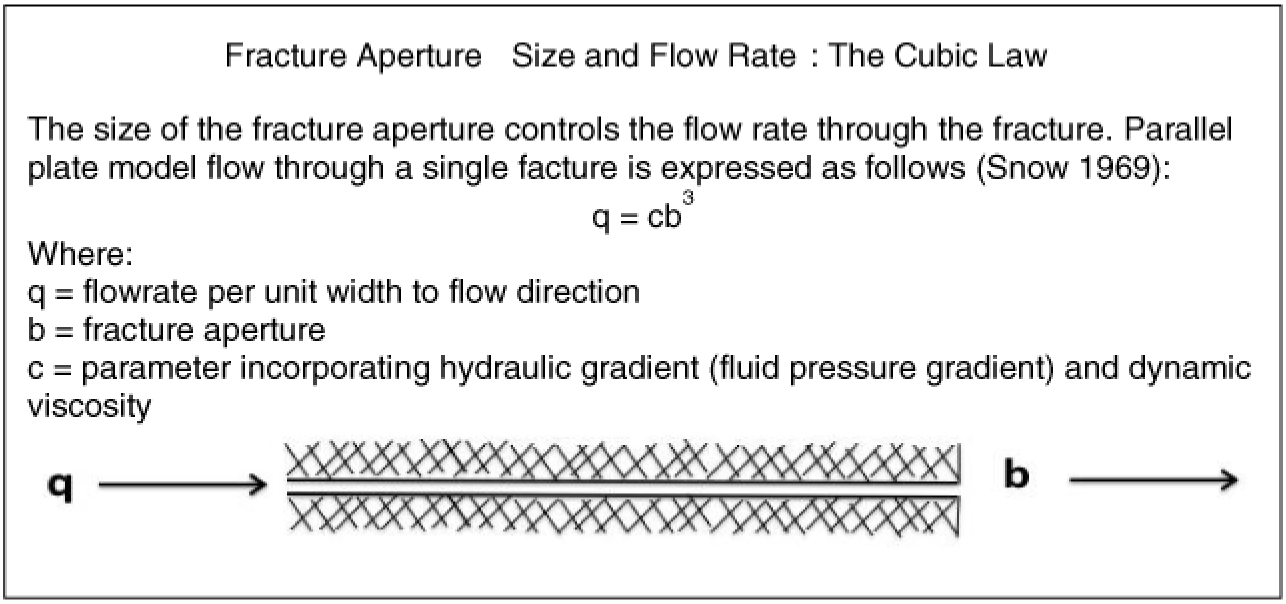


Figure 3-5. Fracture aperture and flow rate.

Assuming all other fracture characteristics are equal, the mean fracture aperture size (b) is the feature that controls the specific discharge. At the site-wide scale, a single, high-aperture fracture may dominate flow over a large number of fractures with much smaller apertures (Shapiro 1987).

An aperture's size may vary significantly along a fracture, causing flow channeling within the fracture and deviations from the general cubic law. Additionally, fracture apertures can contract or expand or vary over time due to mineral dissolution or precipitation (resulting in infilling). Modifying subsurface conditions with hydraulic depressurization or pressurization, heating, and introducing chemicals and microbes (solutes and particles) can influence aperture configuration and flow potential. For example, infilling in a fracture reduces the effective aperture of the fracture, which leads to a proportional reduction in the flow capacity. Fracture infilling may be the result of a variety of phenomena, including sedimentary deposition, chemical precipitation, weathering, biofilms, or cementation. The degree and type of fracture infilling can change with time as the processes of weathering, biofilm growth, and sedimentation may vary during the life cycle of a project. For example, infill material has its own hydraulic properties that may affect flow (see Chapter 4 regarding lithogeochemical effects of fracture infilling or rock matrix). Furthermore, some in situ treatments can leave residual material that limits aperture sizes.

3.1.4 Length

The longer the fracture, the further a fluid volume can travel unimpeded. Longer fractures are more likely to intersect other fractures, increasing the potential flow-field volume and overall distance the fluid can travel.

3.1.5 Density

Fracture density describes the degree or intensity of fracturing and can be represented as the linear density (per unit length), areal density (per planar surface area), or volumetric density (per unit rock volume). The more fractures there are and the closer they are together, the greater the fracture connectivity and the higher the overall void space in the rock, which translates to higher fluid flow and storage potential. The volume of groundwater flowing through a series of closely spaced, small aperture fractures may be equivalent to the flow through a single large fracture, depending on the aperture size and length.

3.1.6 Fracture Connectivity

A single fracture rarely spans the entire length of an investigated area—the degree to which fractures connect to each other influences the overall flow volumes and patterns. Fractures that do not intersect may be filled with fluid; however, little or no flow may be observed. Collectively, the fractures with the lowest flow capacity in an interconnected system may effectively constrain the volume of flow through that system. Conversely, fractures that intersect allow fluids to migrate along fractures that typically have vector components, with migration both down dip and along strike (not all down dip, then along strike). Groundwater plume delineation is sometimes described as a stair-step pattern because wells are located progressively down dip and along strike (see Figure 3-6; also see (Davis 1966b).

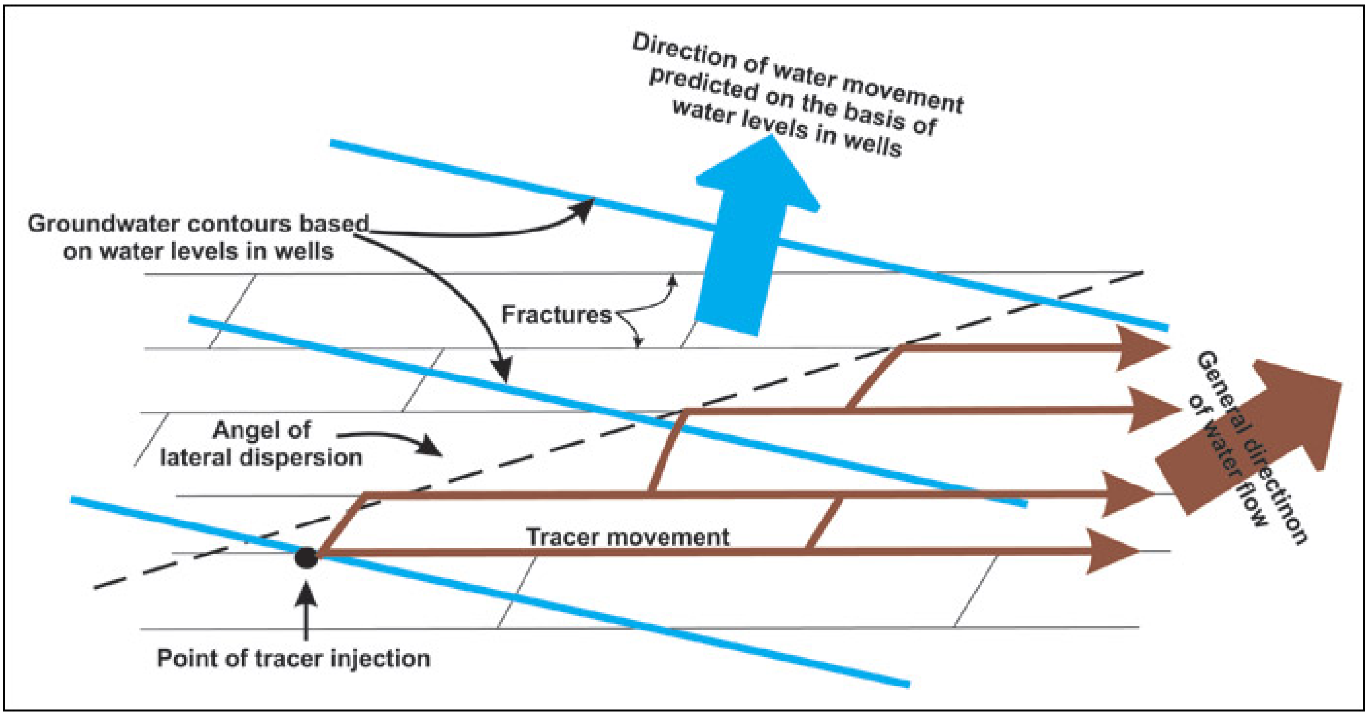


Figure 3-6. Plan view of orientation and connectivity of fractures controlling the overall direction of flow, and the direction of the apparent hydraulic gradient.

3.1.7 Fracture Planarity or Waviness

A planar, open fracture offers fewer barriers to flow, while a planar, closed fracture, such as a horizontal bedding plane fracture experiencing significant overburden pressure, may create an effective barrier to flow. Conversely, the more undulating or wavy, a fracture may be, the more likely it is to be open, especially if the two sides of the fracture are displaced relative to each other.

Local resistance to flow occurs where the fracture surfaces touch. As few as three to five percent of the fracture plane surface area in contact with its corresponding surface may cause significant deviation from the cubic law (Oron 1998), so it is important to consider how waviness may affect the amount of surface contact on a fracture system.

3.1.8 Fracture Roughness

The greater the roughness of a fracture, the greater the effective surface area per unit volume of the fracture resulting in generally greater frictional resistance to flow. With increased fracture roughness, the potential for transported material in the fracture to be trapped by, or to adhere to, the fracture walls also increases. This characteristic can potentially lead to greater infilling and reduced fracture aperture, thereby reducing the volume of fluid flow through fractures by further reducing fracture aperture.

3.2 Fluid Dynamics

Fluid dynamics is the study of fluids in motion. This section introduces fluid dynamics effects on fractured rock flow. The flow of all fluids is influenced by pressure and density gradients, although the focus here is on fluid flow under pressure gradients.

Each individual fracture acts as its own confined aquifer under a unique head or gradient. It is therefore important to understand the differences in head between different fractures, particularly where fractures are widely spaced and connectivity may be low. At some sites, fractured bedrock can be treated as equivalent porous media containing a water table, depending on the combination of fracture density, orientation and spacing, the scale of observation, and the goals of the investigation. Other sites must be treated as discrete fracture networks with one or more piezometric surfaces, and no bedrock water table.

Open boreholes, which penetrate discrete fracture networks, have unique hydraulic characteristics compared to wells penetrating equivalent porous media or unconsolidated materials. Figure 3-7 is a cross-sectional view of three open bedrock boreholes in a generalized hydrogeologic setting. These boreholes are illustrated in more detail in Figures 3-8 through 3-11, which shows several possible hydraulic conditions of transmissive fractures within bedrock. For simplicity, the fractures are depicted as horizontal, although similar conditions are found in dipping fractures.

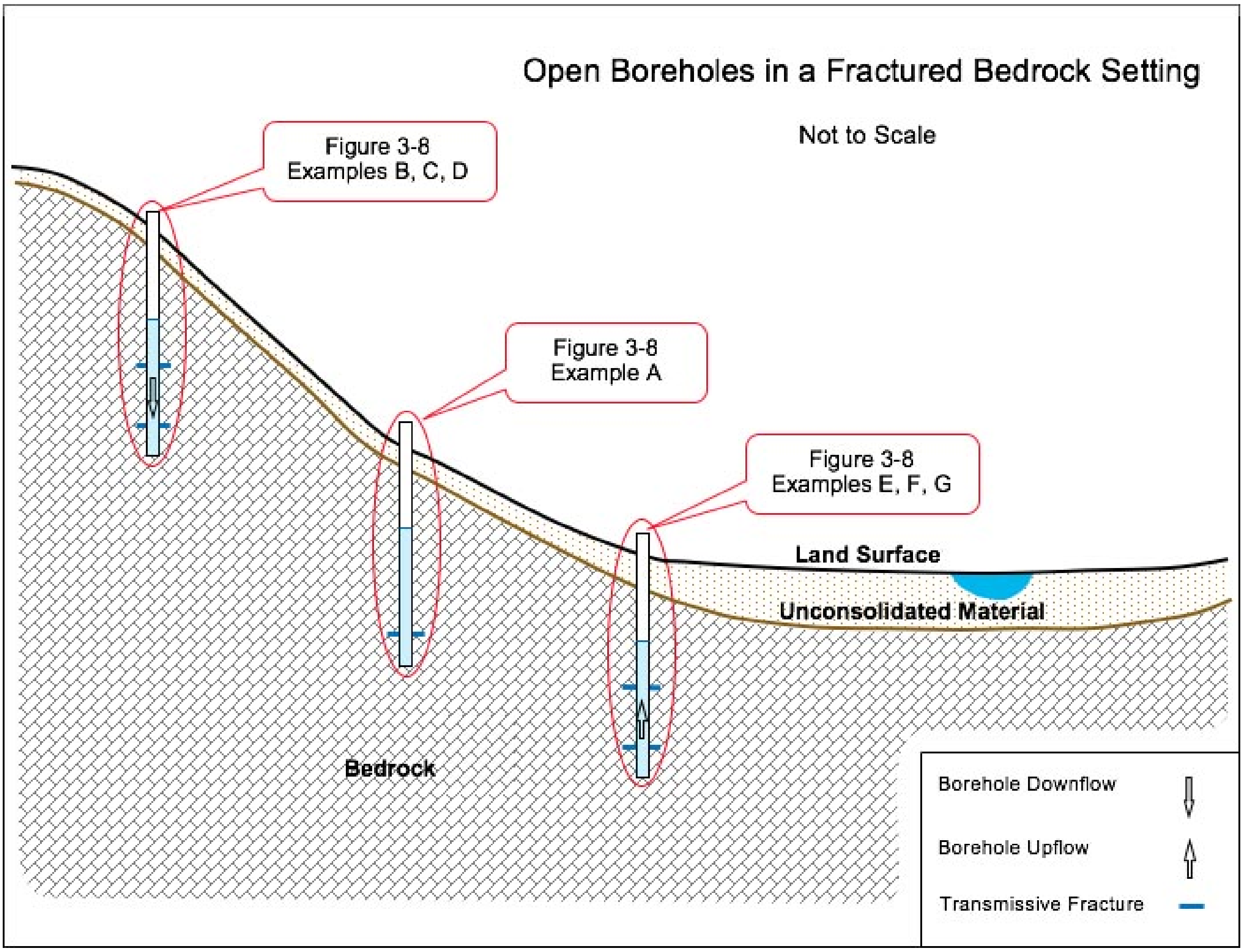


Figure 3-7. Open boreholes in a fractured rock setting.

Figure 3-8 illustrates the simplest case of an open borehole piercing one fracture. The fracture is, in effect, a confined aquifer, so the static water level in the borehole equilibrates at the piezometric surface (head) of the fracture. Disregarding weather-related effects, there is no natural vertical flow within the borehole. This condition could be encountered in areas of groundwater recharge or discharge.

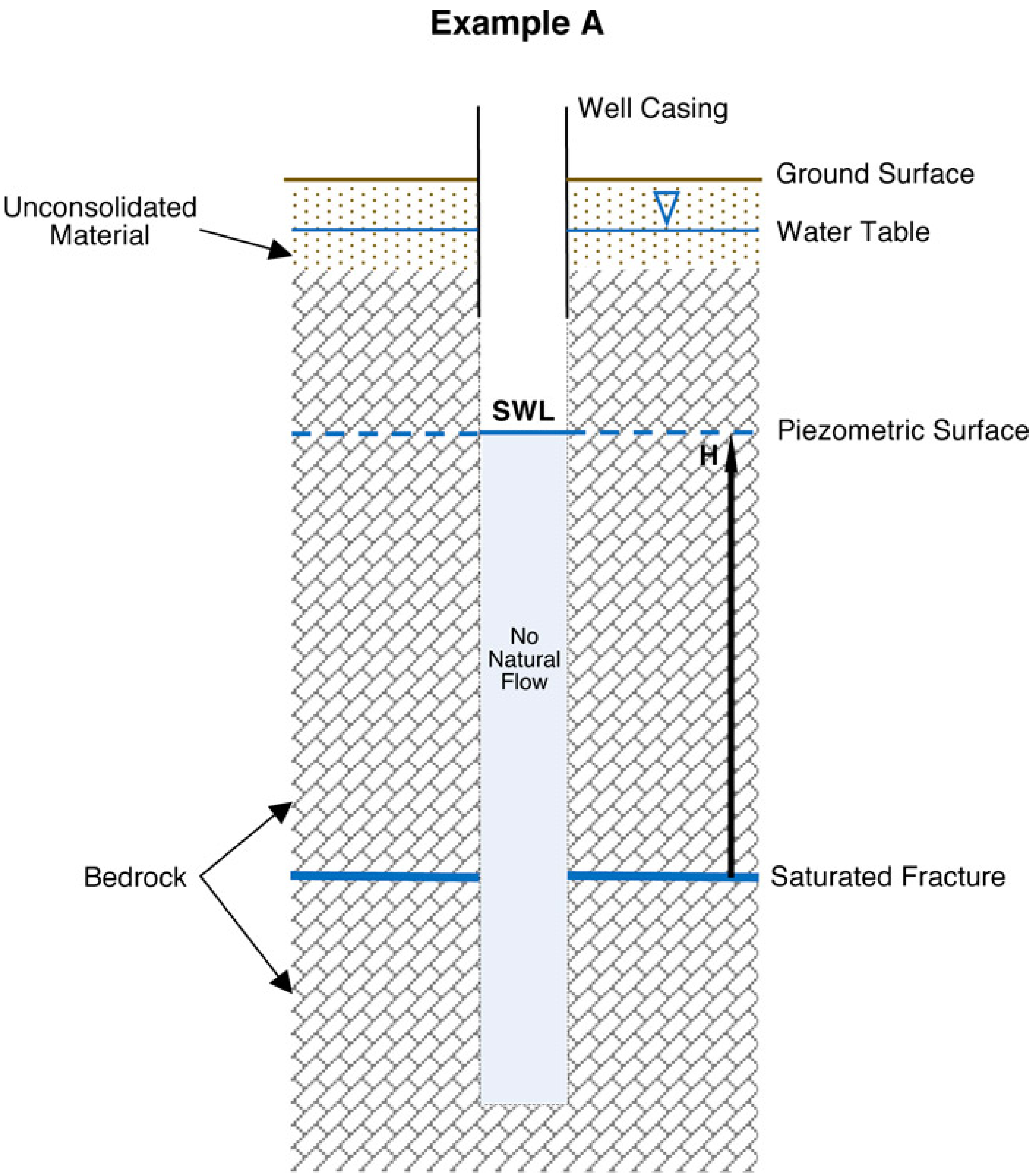


Figure 3-8. Open borehole piercing one confined fracture, no natural borehole flow (Not to Scale) H = Head; SWL = Static Water level

The same principles apply to multiple fractures, with respect the relationships among aquifer transmissivity, head, and water level in a well penetrating a multiaquifer system (Sokol 1963). Figure 3-9 illustrates conditions that would be encountered in a dual-fracture system. Upon drilling through two fractures having different heads, a static water level (SWL) emerges that represents the piezometric surface of neither fracture. The SWL is at an average position of the two heads and is shown in Example B to be at the midway point between them. The SWL of a multifracture (and multiaquifer) system is a function of the heads and transmissivities of the fractures (aquifers).

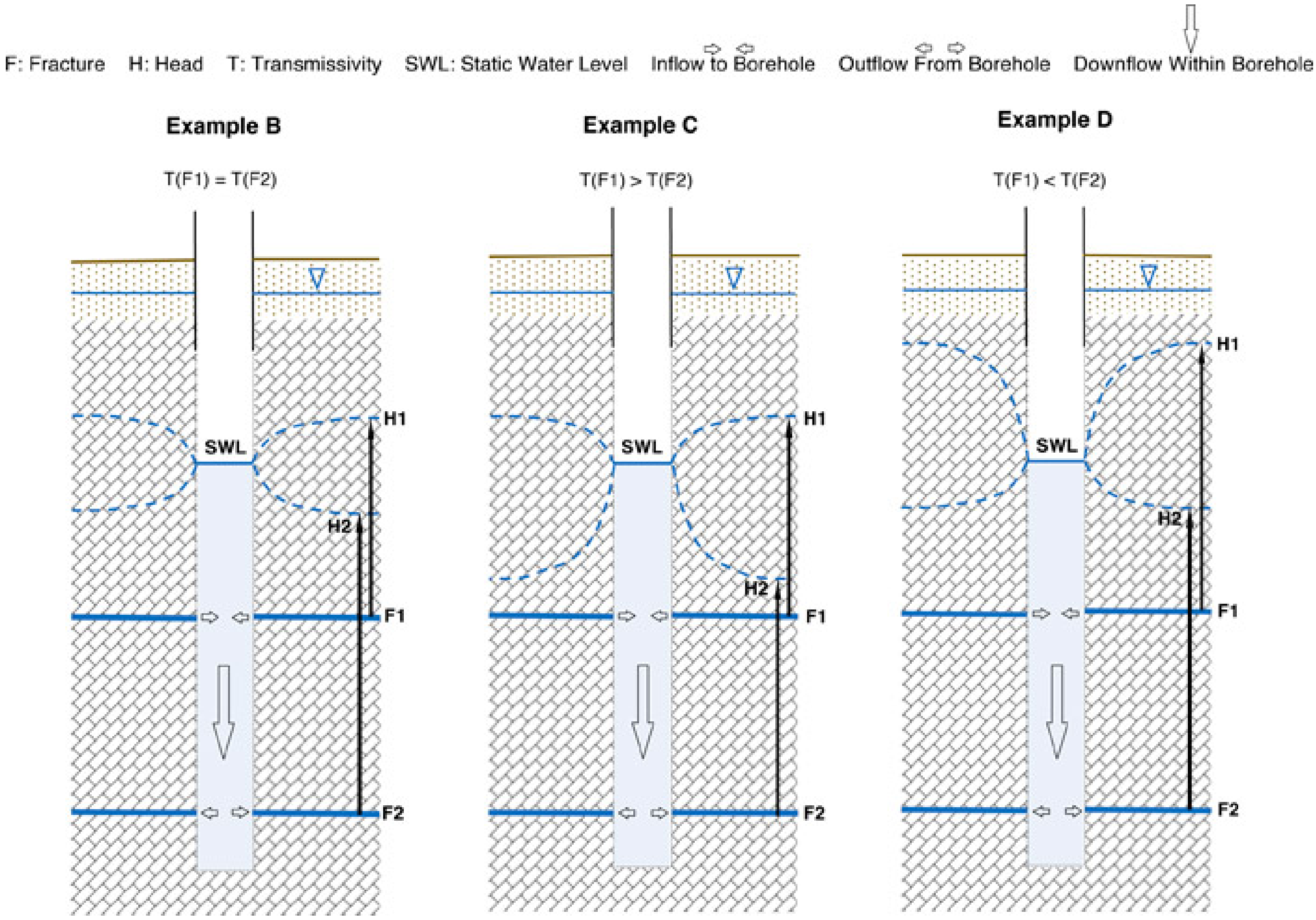


Figure 3-9. Open borehole piercing two confined fractures, natural borehole down flow.

The head in multiaquifer wells is described using the following relationship (Sen 1989):

$$H_w = \sum T_i H_i / \sum T_i \quad (i = 1, 2, \ldots, n)$$

Where ∑ is the "…summation of discrete variables from $i = 1$ to $i = n$" (the number of fractures and corresponding transmissivities), H_w is "…a common steady-state piezometric level…" (the SWL), T is transmissivity and H is head.

Through this relationship, the SWL in the borehole is the composite (weighted average) head of the individual heads (piezometric surfaces). The composite head equals the arithmetic average of individual heads only when the fractures (aquifers) have identical transmissivity values (Sen 1989). In Figure 3-9, Example B, the transmissivities of Fracture 1 and Fracture 2 are equivalent, T(F1) = T(F2), so their respective heads are equidistant from the SWL. Because the fractures have different heads, there is a natural hydraulic gradient. Until the emplacement of the borehole, there was no permeable pathway interconnecting the fractures. A pathway was created when the borehole became part of the local hydraulic system. The head differential (gradient) combined with the pathway enables vertical flow to take place within the borehole. In this example, water enters the borehole from the high-head fracture (F1), flows down the borehole and exits through the low-head fracture (F2). The condition of a high-head fracture located above a low-head fracture is suggestive of a groundwater recharge area. The piezometric surface of F1 takes the form of a cone of depression because it is losing water to the borehole. Conversely, the piezometric surface of F2 takes the form of a cone of recharge because it is gaining water from the borehole. The piezometric surfaces are mirror images of each other because the fracture transmissivities are identical.

In Figure 3-9, Examples C and D represent similar conditions except that the transmissivities of fractures F1 and F2 are not equivalent. Consequently, the piezometric surfaces are not mirror images of each other. Example C illustrates piezometric surfaces that would occur if the transmissivity of F1 > F2. The SWL is weighted toward the head of the more transmissive fracture, F1. In Example D the transmissivity of F1 < F2. Therefore, the SWL is weighted toward the head of F2.

Figure 3-10 illustrates the same relative transmissivities as the previous three examples, except that the gradient and borehole flow direction are reversed. Borehole upflow is depicted in these examples. The condition of a low-head fracture located above a high-head fracture suggests a groundwater discharge area. In a case study of an investigation at the University of Connecticut Landfill, borehole geophysical testing revealed single, double, and triple fracture sets having upflow, downflow, convergent flow, and divergent flow (Johnson 2005).

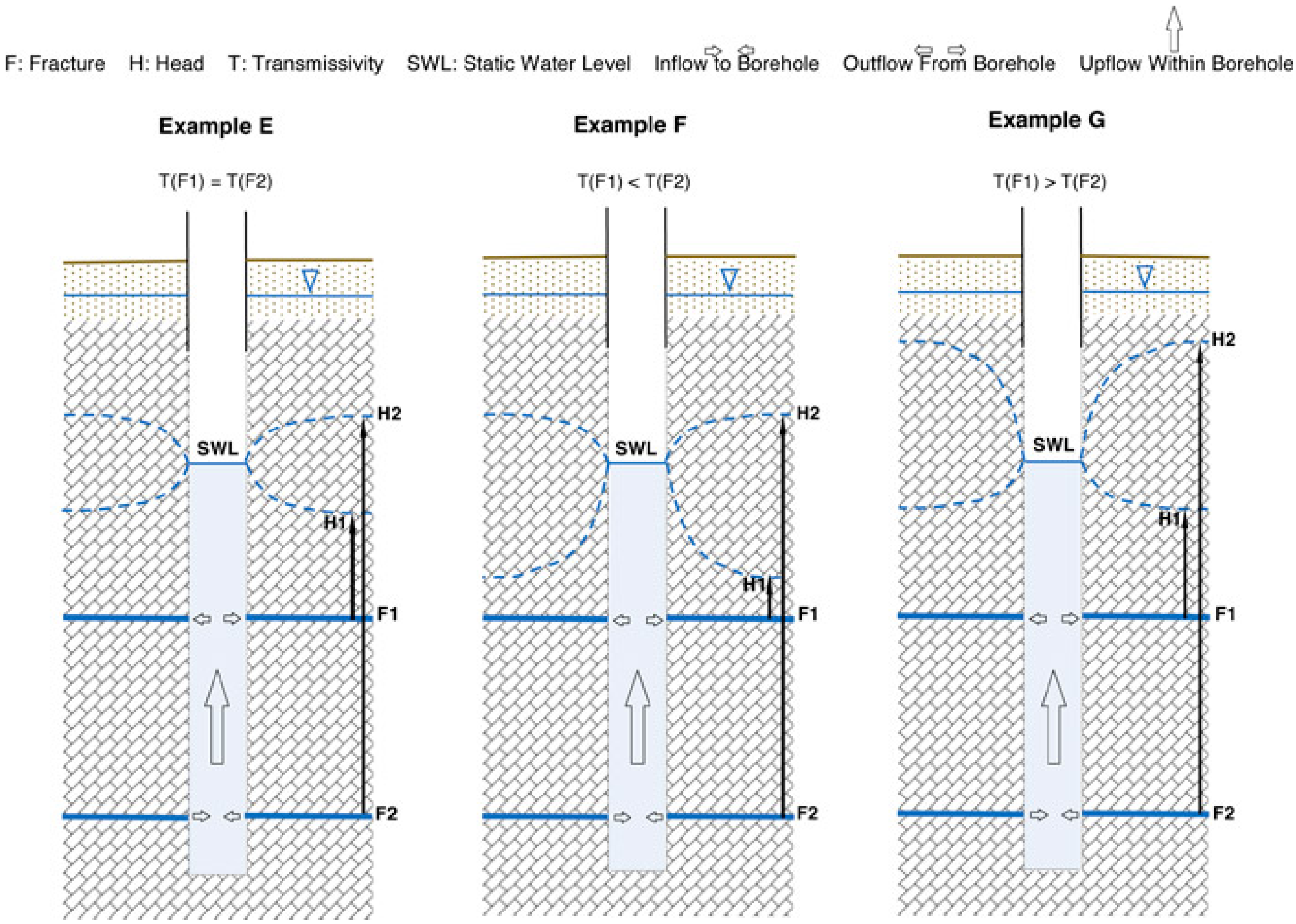


Figure 3-10. Open borehole piercing two confined fractures, natural borehole up flow.

Figure 3-11 illustrates what would be expected if the borehole in Figure 3-9, Example B were pumped down to a point where the pumping water level (PWL) was below the head of Fracture 2 (H2). The piezometric cone of recharge associated with F2 inverts and becomes a cone of depression, because F2 is now contributing water to the well. F1 continues to contribute water but its cone of depression takes on a steeper form. In this example, the water flows vertically in the borehole from both fractures to the pump intake. Note that F2 produces water only because the PWL is lower than H2. If the PWL were higher than H2, then only F1 would produce water.

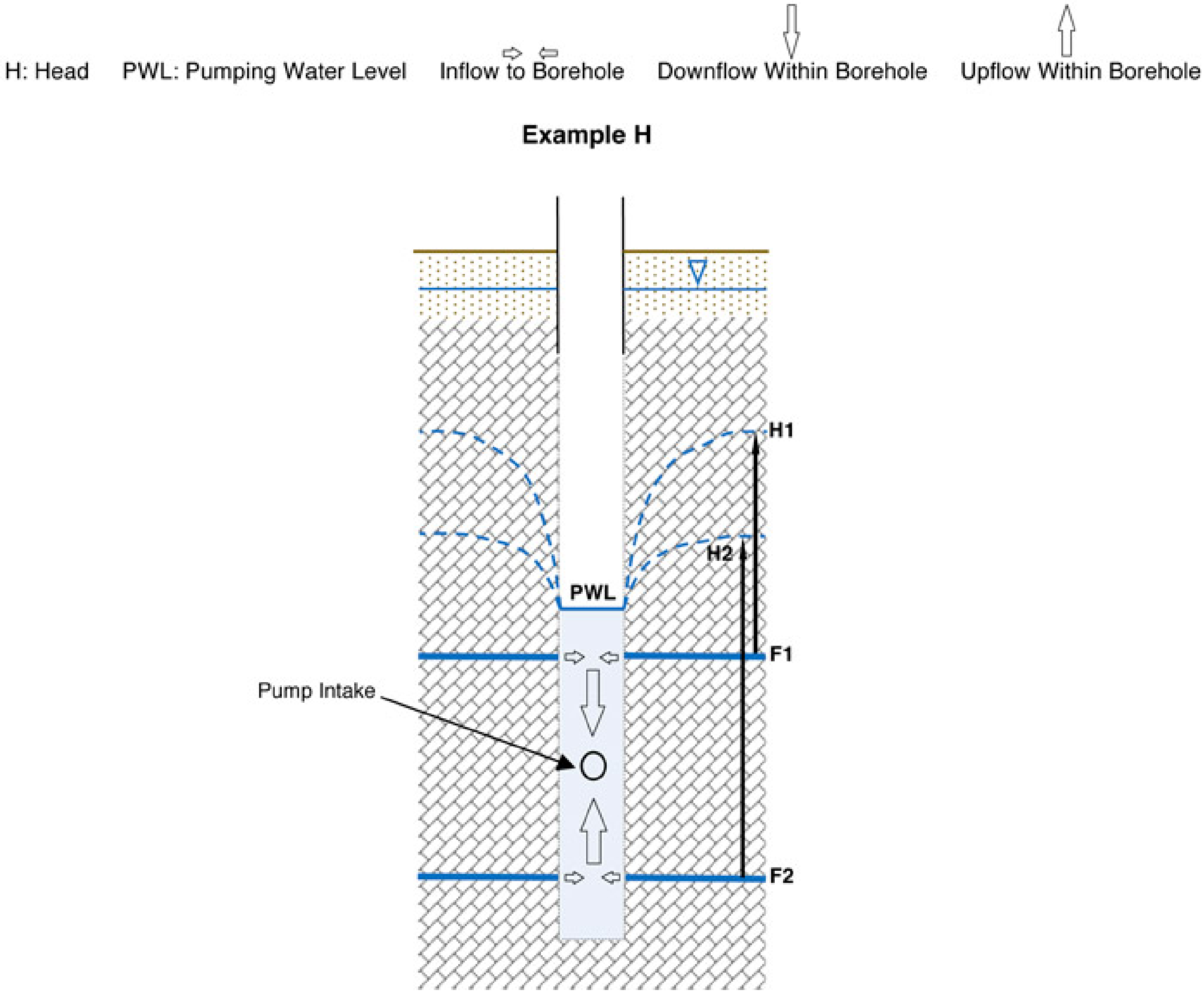


Figure 3-11. Open borehole two confined fractures pumping condition (not to scale)

In the preceding examples (B through G) of dual-fracture boreholes under steady-state conditions, flow occurs due to the head difference between transmissive fractures. If F1 and F2 had the same head, by being connected by another fracture, they would have a common piezometric surface and there would be no natural borehole flow.

Fluid flow in the subsurface can be characterized in terms of the volume of flow through a unit cross-sectional area under a certain pressure differential across two points in the flow field – in effect, Darcy's Law. Darcy's Law assumes the subsurface acts as a continuum and that what is measured at one scale applies at other scales of the system. Using Darcy flow assumptions for a complex fractured rock system may or may not lead to a representative conceptualization of the flow system, depending on the degree of fracturing and of interconnectedness and on the scale of observation.

Fluid flow can be characterized as linear or laminar, and can be modeled using Darcy's Law. Conversely, fluid flow can also be characterized as nonlinear or nonlaminar (not necessarily following Darcy's Law) or turbulent (non-Darcian). For example, flow in karst and pseudo karst terranes is likely to be turbulent, at least at some locations. Flow in an individual fracture may also behave in a non-laminar manner.

The difference between characterizing laminar flow versus turbulent flow is important when the additional energy loss associated with turbulent flow is significant enough to affect specific discharge. Turbulent flow can also cause greater dispersion of solutes compared to laminar flow. However, turbulent flow on a local scale (mesoscopic) scale can often be approximated at a larger scale regional or macroscopic) scale as laminar flow or Darcian flow without introducing significant conceptualization and predictive error. The larger the fracture relative to the system (scale of the problem) and the higher the gradient across the fracture system being evaluated, the more likely that the flow will not follow Darcy's Law. The effect of scale is depicted in Figure 3-12.

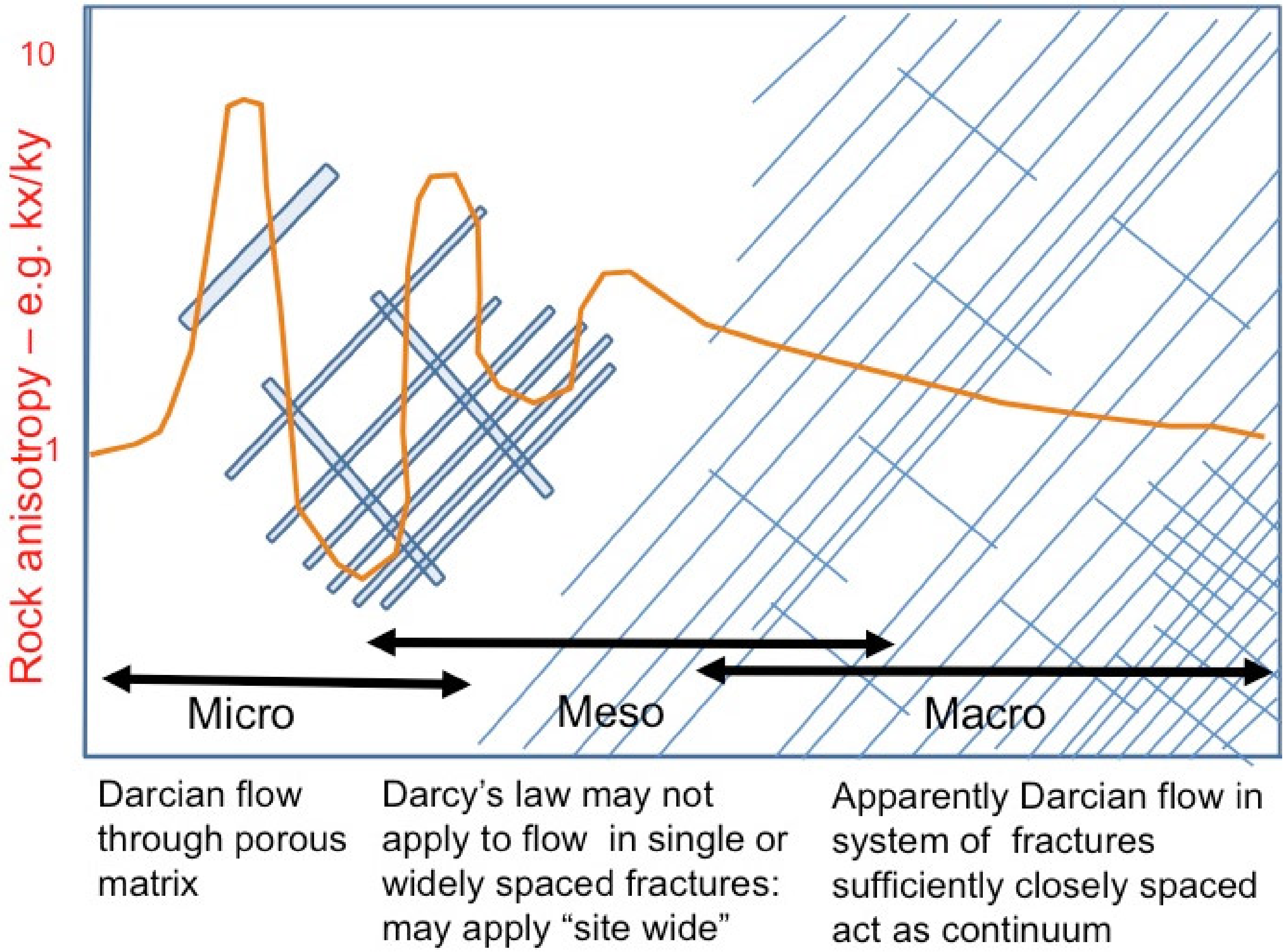


Figure 3-12. Generalized depictions of Darcian and Non-Darcian Flow

3.3 Vapors in Fractured Rock

With respect to the gas phase, a vadose zone can exist above the zone of groundwater saturation and within a fractured rock horizon of interest. Within the vadose zone, the gas phase is continuous and mobile, and the aqueous phase is the secondary, discontinuous, and potentially immobile wetting fluid. In these situations, the gas fluid phase flows through the fractured rock according to the same hydraulic principles as groundwater. Energy gradients and resistance to flow (such as frictional and gravitational forces) govern the flow of the continuous gas phase through fractured rock. Gases typically have very low viscosity and density compared to groundwater, and unlike groundwater, the gas phase is compressible. Thus, gas phase flow behavior can be different from groundwater flow even within the same fractured rock zone of interest. Often, compared to groundwater, the gas phase responds more dramatically to changes in pressure and temperature, even under natural conditions (for example, barometric pressure pumping).

Where liquid-phase organic or inorganic contaminants are encountered in fractured rock, a fraction of the volatile component of the contaminant may partition into the gas phase as solutes and undergo transport with the gas phase. If the concentration of the volatile organic contaminant in the gas phase rises, then the composite density and viscosity of the overall gas phase may cause significant deviation in gas flow behavior.

For the specific case of fractured rock vadose zone overlying saturated fractured rock, and where a volatile organic contaminant release is present in the saturated zone, the lateral and vertical extent of a vapor plume in the vadose zone may have an entirely different geometry from the groundwater contaminant plume mapped in the underlying saturated fractured rock. The volatile organic vapor phase density (and viscosity) is only a small fraction of the groundwater density (and viscosity) and the vapor plume acts as a compressible fluid. The permeability of the vadose zone rock matrix and fractures to gas-vapor flow is much higher compared to groundwater and the gas or vapor flow is more dynamic than groundwater under similar pressure gradients. Furthermore, fracture density is typically highest near the top of the rock column, where vadose zone (gas-saturated) conditions are more likely to be observed. Thus, unlike groundwater or other liquids, the gas phase may flow more freely in different directions and may be more likely to enter a turbulent flow regime more easily. The gas or vapor phase flow potential is more dynamic than groundwater and other liquids.

Because a gas phase is less dense and viscous than groundwater, when a mobile gas phase contacts a mobile groundwater phase, additional complexities may occur. Often dissolved gases that form within fractured rock systems, and under nonequilibrium conditions, can separate out of solution (exsolve) with subsequent formation of gas bubbles (a separate phase). Reactive or destabilizing interfaces within the fractured rock may hasten the formation of gas bubbles. Sufficient gas bubbles can lead to trapped and mobile continuous phases within the groundwater-saturated zone and influence groundwater flow behavior within the rock matrix and fractures.

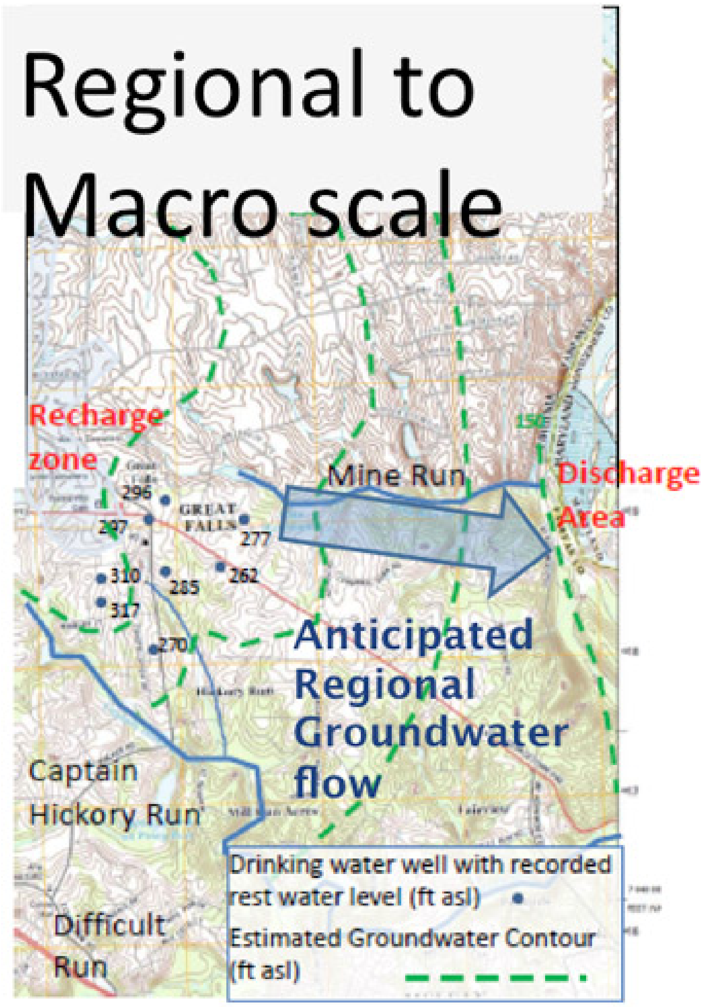
3.4 Role of Scale in Fractured Rock Fluid Flow

The nine characteristics of fractured rock are always present to some degree at the macroscopic, mesoscopic and microscopic scales. Their relative importance to fluid flow varies with the observational scale of interest, and the understanding that certain characteristics may be relevant during site characterization or remediation. The scale of the problem is typically defined by the distance (ideally in three dimensions) between the location of known or potential sources and known or potential receptors. When developing the CSM, it is important to understand the effect of all the relevant scales and incorporate evaluation of their potential effects on groundwater flow at a given site.

3.4.1 Fluid Flow at Macroscopic Scale

The macroscopic scale refers to regional and multisite problems. At this scale, rock characteristics and flow behavior discernible over hundreds to thousands of feet become relevant. These characteristics would be described, for example, on aerial photographs or on a standard 7.5 minute USGS quadrangle topographic or geological map. The terrane information described in Chapter 2 can be used to define the flows likely encountered at this scale.

At the macroscopic scale, it is unlikely that one single structure hundreds or thousands of meters long dominates fracture flow. Instead, flow is more likely governed by a system of interconnected structures of comparable size, orientation and aperture resulting from the same geologic forces (Figure 3-8 and 3-9). Karst features may be defined as a single feature at this scale. The fracture network in each geologic unit is important because the orientation, length, and connectivity of fracture systems control flow at this scale, with flow behaving as a broadly continuous Darcian flow system with degrees of heterogeneity and anisotropy resulting from those characteristics. Where connectivity of fractures is low, highly transmissive fractures may be connected to fractures of much lower transmissivity, causing bottlenecks to flow (Shapiro 2007). In effect, the lower transmissivity fractures become the controlling fractures to overall flow volume.


Regional to
Macro scale
Recharge
zone
296
297
GREAT FALLS
277
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Mine Run
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Anticipated
Regional
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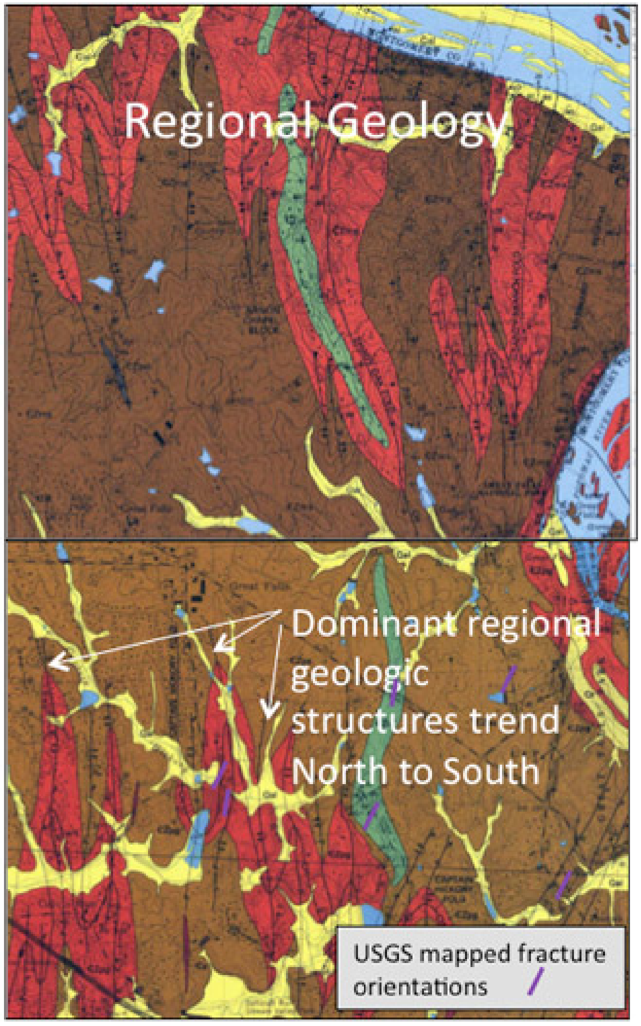
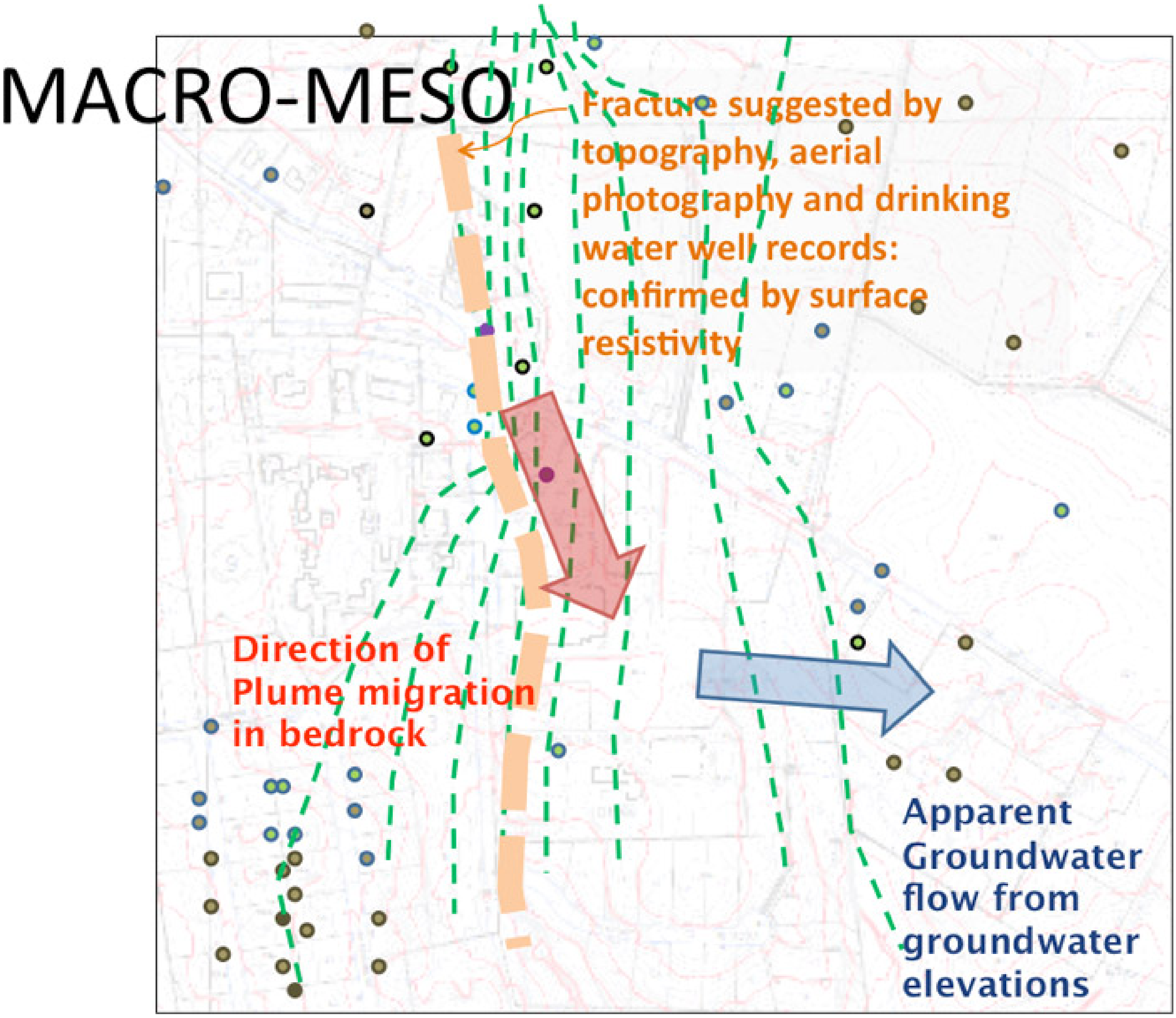
flow
Captain
Hickory Run
Difficult
Run
Drinking water well with recorded
rest water level (ft asl)
Estimated Groundwater Contour
(ft asl)


Regional Geology
Dominant regional
geologic
structures trend
North to South
USGS mapped fracture
orientations



Figures 3-13. Generalized descriptions of flow regimes across the macroscopic and mesoscopic scales, illustrating how rock characteristics can impact flow directions.

Local aberrations in the regional flow field (or mesoscopic scale) can still result from discrete large-scale fracture effects on flow at the macroscopic scale. For example, long fractures are likely to connect with other fractures and are more likely to influence regional (macroscopic) flow and transport. Karst features, fault planes, and bedding planes are the good examples of macroscopic fracture systems that create a regionally influential flow features. Faults can enhance, redirect, or even terminate the continuity of flow depending on the orientation of fractures and on fault character. Many fault zones experience physical or geochemical infilling, restricting fluid flow over time. Therefore, CSMs and investigations for sites with identified fault features should be approached with an open mind in determining the ultimate role the faults play in influencing fluid flow.

3.4.2 Fluid Flow at Mesoscopic Scale

The mesoscopic scale refers to the scale of an individual project site, typically investigated by a number of site-specific boreholes. At this scale, features are typically not large enough to be recognizable on topographic maps or aerial photographs but can be important at the field scale and within and between individual boreholes.

The relative size of mesoscopic fractured rock structures fall on the continuum between large-scale macroscopic features and microscopic features. Figure 3-14 shows a reduction in apparent fracture aperture of one order of magnitude over 30 feet, with a three orders of magnitude reduction in apparent conductivity (as would be anticipated with from the cubic law). Rock characteristics can be deduced from geophysical surveys, observed within a borehole, or examined at a rock outcrop. As fracture density and size decrease with depth, although fracture apertures may remain similar, hydraulic conductivity may decrease with depth as more fractures become infilled. Individual fractures may be interconnected and several discrete flow paths may be present and identifiable within a single borehole (Gupta 1999), with order of magnitude changes in characteristics over small vertical and horizontal intervals.

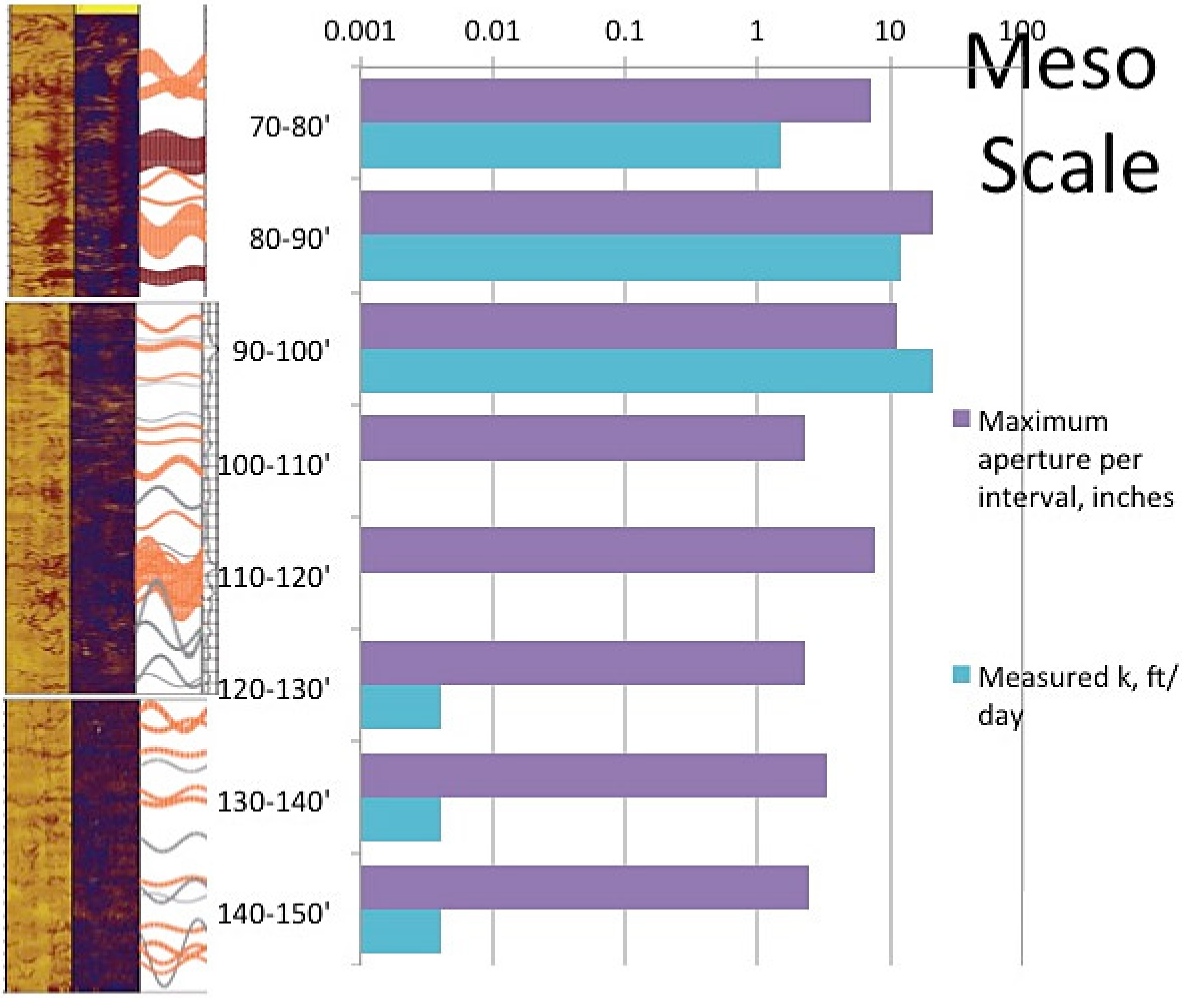


Figure 3-14. Generalized depiction of changes in flow characteristics over the mesoscopic scale [*relationship of aperture size plotted and meaured hydraulic conductivity, K = hydraulic conductivity*]

Fractures with low connectivity and discrete flow paths are often under separate pressure gradients at the mesoscopic scale and resolving these different pressure gradients is an important part of the site characterization process. The pressure gradient/head in particular fractures in one vertical sequence can vary significantly over small distances and respond in dramatically different ways to external events, such as pumping or rainfall, as shown in Figure 3-15.

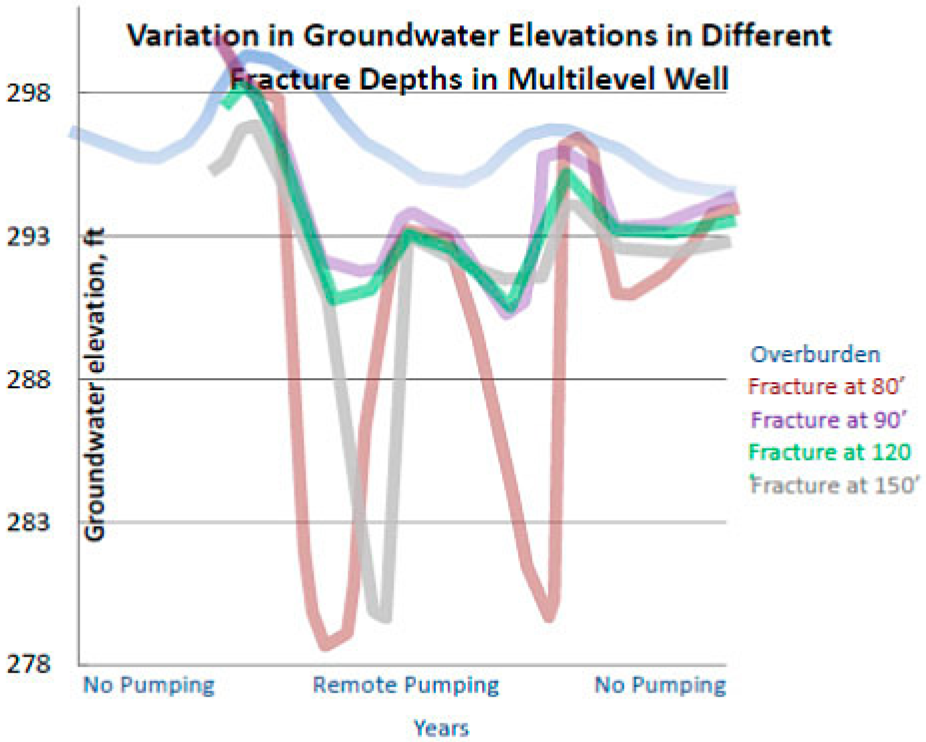
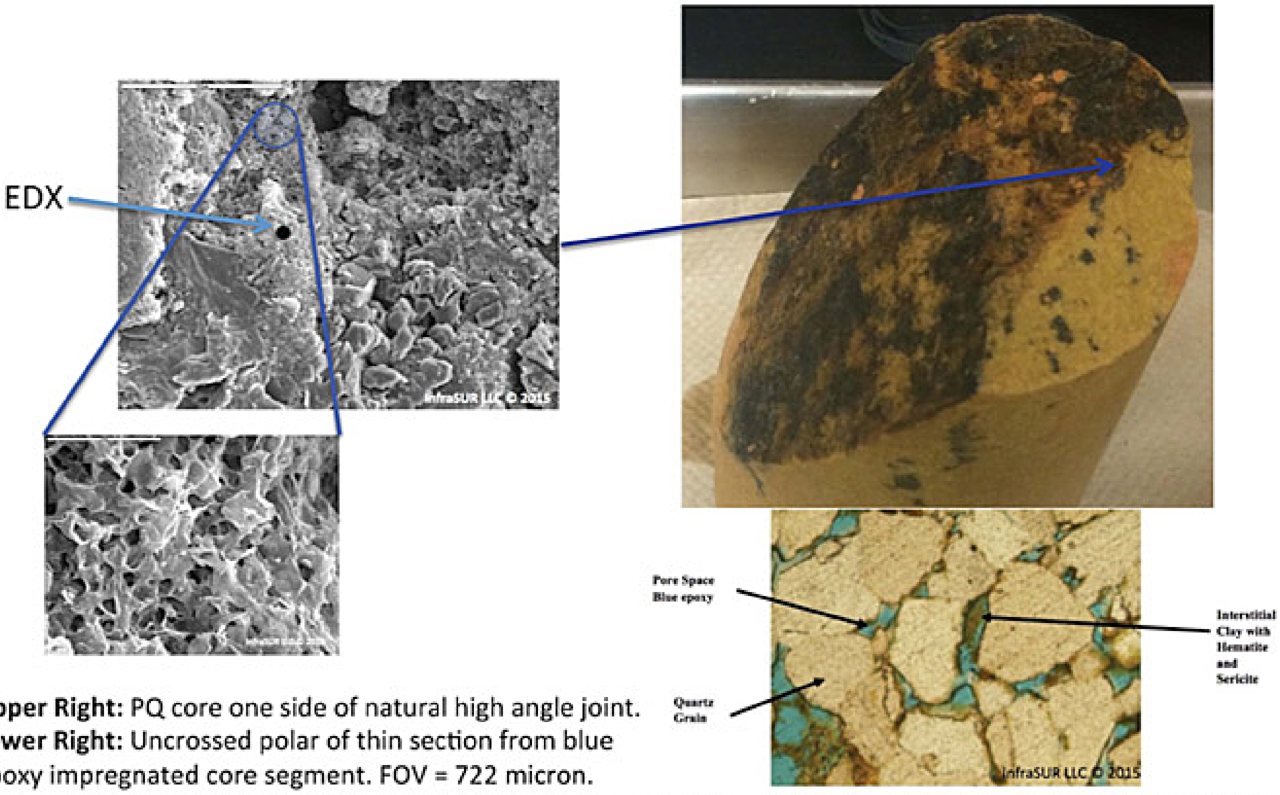


Figure 3-15. Variation of groundwater elevations in different fracture depths in a multi-level groundwater monitoring well.

As discussed in Section 3.1.2, aqueous fluid flow in these structures can be thought of as flowing down the face of the structural feature (down dip) above the water table and along the face of the structure (along strike) at and below the water table (Figure 3-6). Fracture orientation (strike and dip), aperture, density, length, and connectivity are the most important characteristics to consider at this scale (see Figure 3-1). At this scale, turbulent flow may occur in individual fractures. Fate and transport of contaminants is primarily through advection, entrainment, or both (Figure 3-1) and is described in detail in Chapter 4 .

3.4.3 Fluid Flow at Microscopic Scale

Microscopic features can represent significant storage of groundwater and contaminants, and their interaction with larger scale features can control fluid mobility (permeability of rock matrix) and thus contaminant mobility. Compared to the mesoscopic and macroscopic scales, high physical property contrasts or chemical/pressure gradients are likely present over small distances; however, these properties may be difficult to evaluate. Often, characteristics at this scale are evaluated in the laboratory or inferred from the available literature.



Upper Right: PQ core one side of natural high angle joint.
Lower Right: Uncrossed polar of thin section from blue epoxy impregnated core segment. FOV = 722 micron.
Upper Left: SEM image. Scale bar is 50 micron. Black dot indicates location of EDX analysis. EDX indicates mixture of manganese and iron oxides and clay or Mn/Fe bearing smectite clay.
Lower Left: SEM image. Scale bar is 10 micron. Note honeycomb morphology of spongy oxide material with pores of nominal 1 micron diameter.

Figures 3-16. Matrix and fracture features at the microscopic scale, which may influence flow within fractures.
Source: InfraSUR, LLC

The microscopic feature of interest can vary depending on its spatial orientation of the feature relative to its surroundings, (such as the location in the matrix that is adjacent to the fracture surface). The same fracture characteristics (aperture, orientation, length, and density) used for mesoscopic and macroscopic scale applies at the microscopic scale (Figure 3-1). At the microscopic scale, characteristics of the rock matrix may be important; for example, matrix porosity, including grain size, pore shape, pore connectivity, crystal structure, cleavage, and microfractures (such as microcracks or microjoints). Microfractures may exist in all rocks, including rock that appears to be fresh or unfractured at the mesoscopic and macroscopic scale (Figure 3-16).

Flow at the microscopic scale occurs through microfractures or through the rock matrix. It may not be possible to differentiate flow through microfractures or the rock matrix. If the microfractures or pore space connectivity is sufficient, then advective flow may occur driven by pressure gradients at the regional and local scales (for example, between low and high permeability fractures). Where connectivity is less well developed, capillary flow may dominate.

Fluid interaction at the microscopic scale can influence flow at larger scales. Flow through the matrix and within fractures continually changes, and the geochemistry continually varies, which causes dissolution and precipitation of minerals as groundwater flows through the matrix and within fractures. Factors influencing these changes include: pH, reduction/oxidation, solubility limits, chemical concentrations, aqueous geochemical and biogeochemical influences, pressure, temperature, fluid/rock interaction and residence time, mineral alteration zones, and chemical weathering (Sausse 2001). Conversely, on one end of the water/rock interaction spectrum is the removal of rock mass to enlarge voids, and on the other end is mineral precipitation to the point where filled-in fractures may become barriers to flow (Neuman 2005).

Upon identifying the dominant characteristics influencing fracture flow, the next step in refining the CSM is to evaluate the chemical fate and transport of contaminants within these affected media. Contaminants may be transported by a variety of mechanisms (such as advection, dispersion, diffusion, and entrainment), which are further described in Chapter 4.

4 Chemistry: Fate and Transport

The term "fate and transport" describes how chemicals entering the subsurface from point or nonpoint sources relate to groundwater concentrations elsewhere. The behavior of contaminants in rock formations depends on the physical and chemicals properties of the contaminants and on the rock characteristics. This chapter presents an overview of fate and transport mechanisms and discusses how the unique properties of individual chemicals or mixtures of chemicals influence fate and transport in a fractured rock environment. Understanding the fate and transport of contaminants within various rock types and the hydraulic characteristics of the rock provides a basis for developing a more reliable CSM.

4.1 Fate and Transport Mechanisms

A challenge with managing contaminated fractured rock sites is determining the direction and rate of contaminant transport within the subsurface. Because fractured rock is anisotropic and heterogeneous, fluids travel at variable rates within the rock, including potentially rapid movement of contaminants over long distances through preferential flow paths (secondary porosity). As a result, hydrogeologic and geochemical equations and models developed for homogeneous porous media may fail to characterize or predict contaminant fate and transport for these systems.

The fate and transport of contaminants within fractured rock involves complex processes that depend on interactions among the physical and chemical properties of the contaminants and the rock, as well as the hydrology of the fracture flow. As contaminants flow through the subsurface, they are subjected to a range of physical, chemical, and biological processes that disperse, transform, or degrade the contaminants. Furthermore, different contaminant classes (such as volatile organic compounds or metals) behave differently in the subsurface based on their physical and chemical properties.

The discussion of fate and transport mechanisms is organized as follows:

- movement through fractures
- diffusion into and out from the rock matrix
- retardation (sorption and desorption)
- natural attenuation through biotic and abiotic transformation
- volatilization (unsaturated zone only)

4.1.1 Movement through Fractures: Advection, Capillary Flow, Dispersion, and Diffusion

Four mechanisms control the movement of contaminants through fractures: advection, dispersion, diffusion, and capillary flow.

Advection. Advection is the transfer of a contaminant by the typically horizontal flow of a fluid (either groundwater or the contaminant). Advection is often the primary mode of contaminant transport under single-phase transport (dissolved phase) or multiphase transport (simultaneous water and NAPL, or water and gas migration). By this mechanism, movement of the contaminant occurs because of bulk fluid motion under the influence of gravity or hydraulic pressure and gradients. While advection is a dominant transport mechanism in porous media, the rate and direction of advection in fractured rock can vary significantly over short distances.

In fractured rock, advective transport is controlled by several criteria including: size, roughness or asperity, planarity or waviness, orientation, and connectivity of the fractures within the host rock in relation to the aquifer hydraulic gradient or pressure. For example, interconnected fractures in limestone, enlarged by dissolution, can have high hydraulic conductivity values (10^{-1} to 10^{4} m/day) compared to a fractured shale, where the fracture aperture and interconnectivity may be smaller and result in lower hydraulic conductivity values (10^{-5} to 10^{-3} m/day). Therefore, for rock types characterized by comparatively large fractures that are interconnected or extend for hundreds of feet, advective contaminant transport can potentially occur over a longer distance and in a short period of time. Caves thousands of feet long are capable of transporting contaminants rapidly.

Capillary Flow. While advective flow is the dominant transport mechanism in large aperture fractures, when multiple continuous phases are present (such as water and NAPL), capillary flow or film flow may become important with decreasing aperture size. Capillary flow of contaminants (the flow of a contaminant into narrow fractures without the assistance of and often in opposition to gravity) is more significant over shorter distances. Capillary flow can dominate flow conditions in small aperture fractures or support thin films along the walls of larger fractures. Within a developed fracture system capillary, or film flow, can travel up to 1,000 times faster than the typical pore water velocity (NRC 2001). Depending on size, orientation, and interconnectedness, capillary or film flow can short circuit matrix flow and substantially increase the transport rate and distance, particularly within the vadose zone. This type of fracture flow can be important in the movement of NAPL.

Diffusion. Diffusion operates independently of bulk flow and results from molecular movement of contaminant solutes within a media from areas of higher chemical concentration to areas of lower chemical concentration. Diffusion within fractures is more significant over shorter distances (such as centimeters to meters).

In porous media with low hydraulic conductivity, contaminant diffusion within fluid-filled interstitial pore spaces can play a major role in contaminant migration in the subsurface. In fluid-filled fractures, as the hydraulic conductivity of fractured rock mass increases with increasing fracture aperture or fracture frequency, the effects of diffusion within the fracture on contaminant transport are overshadowed by physical transport mechanisms (advection, dispersion, and capillary flow).

4.1.2 Diffusion and the Rock Matrix

Matrix diffusion is a significant mechanism by which contaminants may enter a rock matrix with appreciable pore space, such as sedimentary rocks. In this process, elevated dissolved concentrations present in the secondary porosity (within fractures) are partitioned toward areas of low concentration in the rock matrix. When a plume is first entering a fractured rock zone, diffusion of contaminant molecules into the matrix retards the advection transport of the plume. The rate of matrix diffusion and the extent of penetration into the rock is controlled by a complex relationship depending on the following:

- contaminant concentration gradient
- contaminant physical and chemical characteristics
- rock matrix biogeochemistry
- rock matrix porosity and tortuosity (a property characterized by many turns)
- degree of saturation
- fracture flow rates, which influence the residence time of the contaminant in the fracture (amount of time for rock matrix diffusion to occur)

Once the contaminant is diffused into the rock matrix, the process of diffusion works in reverse (which is called "back-diffusion") and releases the contaminant stored within the rock matrix back into the fracture. Back-diffusion is a dynamic phenomenon, causing the passing plume to persist at a point of observation, albeit at a relatively low concentration, longer than it would otherwise, even if the contaminant is removed from the fluid within the fractures, This process increases effective plume longevity and, if not accommodated, can greatly delay remediation times frames. If, however, the flow in the fracture is very high relative to the flow in the porosity, the back-diffusion may be diluted and thus not be an issue.

4.1.3 Retardation: Sorption and Desorption

Retardation is the result of sorption of contaminants to the sides of fracture walls and the rock matrix, which varies with the amount of clay minerals or mineralogy of the rock within fracture surfaces. This process slows the movement of contaminants through fractured rock. Retardation affects the migration of the center of mass of the plume. The rate of contaminant migration varies with dispersion, because retardation is less significant for the more permeable pathways.

Naturally occurring organic matter also affects retardation. Organic carbon (f_{oc}) may line fractures (secondary porosity) or may occur within the rock matrix (primary porosity). Organic matter affects fate and transport and ultimately the remediation of a contaminant, for the following reasons:

- Organic matter retards contaminants so that the rate of dissolved-phase contaminant migration is less than the groundwater velocity.
- Over time, the mass of contaminant in the rock matrix can be greater than in open fractures.
- The time required to remediate the site may be controlled by desorption from organic carbon in the rock matrix and back-diffusion of the dissolved-phase contaminant. Higher f_{oc} in the rock matrix prolongs the time frame for removing the contaminants.

When organic carbon is suspected to be present, organic carbon analysis should be considered. Organic carbon is possibly present at sites underlain by sedimentary, igneous, or metamorphic rock; however, it is more likely to occur in sedimentary rock. Rocks that have undergone crystallization (most igneous and metamorphic rocks) have greatly reduced organic carbon and demonstrate limited retardation as a function of contaminant sorption. Analysis of organic carbon should be performed for sites where NAPL or dissolved contaminants occur within fractured igneous or metamorphic rock that exhibits primary porosity.

For metals, retardation can occur through sorption onto surfaces such as ferric iron oxy-hydroxides, carbonates, and silicates. For example, trace metals such as cadmium, nickel, lead, and zinc can sorb or complex with natural mineral forms, as well as with secondary precipitate forms such as ferric iron oxy-hydroxides or hydroxysulfates. These secondary precipitates typically form within fractures or underground mine voids because of oxidation or infiltration of precipitation (see Section 4.1.6). The degree of sorption onto these surfaces also depends on pH and redox state.

Retardation of trace metals may be a significant factor in the fate and transport of contaminants at some sites such as mines, industrial sites, or sites where mixed organic contaminants have been released (for example, where DNAPL is also affected by metals). For example, intentional oxidation of a plume of organic contaminants could result in geochemical changes to the rock matrix and lead to the release of trace metals into groundwater. In contrast, the presence of metals comingled with organic contaminants could, due to the competition for surface sorption sites on organic matter, result in the increased mobilization of organic contaminants.

4.1.4 Natural Attenuation through Biotic Transformation

Biotic transformation involves metabolic and enzymatic pathways, which may occur as a component of natural attenuation within fractured rock. For fractured rock, the availability of surface area for microbial attachment and lower organic carbon content (compared to porous media) may limit the rate and capacity for biotic transformation. ITRC provides additional information on aqueous conditions that favor natural attenuation through biotic transformation chlorinated solvents (ITRC 2008).

Naturally occurring organic matter, or another contaminant release such as petroleum hydrocarbons, may provide a carbon substrate in fractured rock for some forms of biotic transformation, such as reductive dechlorination of chlorinated solvents. For metals, biotic transformation may alter the geochemical state of the aqueous environment and that of the metal contaminant to a more stable (nonmobile) form. With the presence of organic carbon, sulfate-reducing bacteria (SRB) (ITRC 2003) can reduce sulfate to sulfide and form metal sulfide precipitates to attenuate the metals from solution.

Biotic transformation may also be referred to as biotransformation, biodegradation, and biocatalyst (Suthersan 2005). This biotic process may occur due to indigenous microorganisms or cultured microorganisms added to the subsurface to degrade contaminants. Four common types of transformations that can occur in fractured rock are described in the following sections.

Reduction and oxidation (redox) reactions ▼*Read more*

Microorganisms can gain energy for growth by coupling reduction-oxidation reactions by electron transport systems. DNAPL and dissolved chlorinated aliphatic hydrocarbons, such as PCE, can serve as electron acceptors in these biocatalyzed reactions.

$$CCl_4 + 2H_2 \rightarrow CH_2Cl_2 + 2H^+ + 2Cl$$

For example, under anaerobic conditions, alternative electron acceptors, including nitrate, nitrite, Mn (IV), iron (III), sulfate, and CO_2, can be used by specific groups of microorganisms. Using these alternative acceptors in electron transfer bioprocesses is termed anaerobic respiration. In anaerobic environments, hydrogen can also serve as an electron donor for the reduction of contaminants. Halorespiration refers to biological reduction of organic solvents to produce energy for growth. In this process, hydrogen is oxidized while the chlorinated solvent is reduced.

Cometabolism ▼*Read more*

Cometabolism is a fortuitous reaction in which a compound is degraded by a substance that organisms produce for other purposes. The cometabolic process does not benefit the organism producing the substance (such as an enzyme or cofactor). For example, bacteria produce metallocoenzymes, such as cytochrome P450 and iron (II) porphorins, that are capable of dechlorinating carbon tetrachloride. Bacteria produce another class of compounds, oxygenases (including mono- and dioxygenase enzymes), which are among the most important inducible enzymes for cometabolism of chlorinated compounds. Cometabolic transformation kinetics are complex and not well understood. The models developed to describe these kinetics are likewise complex, and often make quite different assumptions about system behavior, growth kinetics, substrate utilization kinetics, and cometabolite oxidation kinetics.

Assimilation ▼*Read more*

Assimilation refers to the incorporation of substances into biomass. In some cases, groundwater contaminants can be converted into biomass by microorganisms. To produce biomass, microorganisms require sources of carbon, hydrogen, oxygen, and nitrogen, as well as trace nutrients. For example, microorganisms can use ammonia (NH_4), nitrate, or nitrite as sources of nitrogen for growth. Although assimilation processes may involve redox reactions, these processes are different from dissimilatory redox reactions because the latter produce energy for the growth of microorganisms. In contrast, assimilatory reactions (anabolic reactions) often require energy. For example, the assimilation of ammonia via the glutamine synthesis reaction utilizes adenosine triphosphate (ATP) (energy), yielding adenosine diphosphate (ADP) and inorganic phosphate (Pi):

$$\text{Glutamate} + NH_3 + \text{ATP} \rightarrow \text{Glutamine} + \text{ADP} + \text{Pi}$$

Sequential transformations ▼*Read more*

Transformation of contaminants in groundwater is often sequential with various intermediates (or degradation products) appearing before the contaminant is completely mineralized. For example, the generally accepted sequence for denitrification is:

$$NO_3 \rightarrow NO_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

The presence of intermediates from sequential transformations is often used as an indicator of contaminant degradation by natural attenuation. For example, in the case of groundwater contaminated with carbon tetrachloride, the presence of chloroform and methylene chloride may indicate that contaminant degradation has occurred. The reaction rates for the various steps in a sequential transformation may be considerably different. Thus, an intermediate in the sequence that is formed quickly, but consumed slowly, can accumulate during sequential degradation.

4.1.5 Natural Attenuation through Abiotic Transformation

Abiotic transformation of contaminants in fractured rock may be an important natural attenuation mechanism for reducing the magnitude and extent of pollution effects. Depending on the contaminant, abiotic transformation (without direct biological transformation) can involve chemical, redox, and electron transfer reactions. An example of a chemical reaction is hydrolysis (such as for 1,1,1-TCA to 1,1-DCE).

Redox reactions are catalyzed or promoted by reactive surfaces such as those associated with certain metals, metal sulfides, and clay particles. An example of an abiotic redox reaction is β-elimination, such as for rapid mineralization of TCE through acetylene. The reactive surfaces may be of basic geologic origin, or derived from abiotic geologic and weathering processes, or from biogeochemical processes. For example, many ferrous sulfides originated as products of iron and sulfate reduction over time. Thus, knowledge of the fracture and matrix mineralogy, morphology, weathering, and microbiology is necessary to assess the potential for redox-based abiotic transformation.

At some sites, rocks with high metal sulfide mineral content, such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), and cinnabar (HgS), can become oxidized, release metals into solution, and generate acidity (low pH and elevated aluminum, iron, and manganese). For mines, this acidified water is often called *mining-influenced water*. In the presence of carbonate or other rock forms that can contribute alkalinity, neutralization or pH increases can occur, resulting in secondary precipitate forms. Secondary precipitates can also form in fractures as seasonal groundwater elevations decrease, leaving a mineral crust in the drying voids. Stability of these secondary precipitates (for example, their potential for redissolution into the aqueous phase) is subject to pH and the geochemistry of the surrounding water and rock matrix when submerged. The lower the pH and water ionic strength, the greater the tendency for precipitates to redissolve. For dried precipitates within fractures, seasonal changes in groundwater elevations (increase) can result in subsequent dissolution of the secondary precipitates, which again mobilizes the metals and potential acidity into the groundwater system. USGS and other sources in the research literature describe the geochemical transformations associated with hard-rock and coal mines, or similar geologies in other nonmine environments.

When heavy metals are present in the subsurface, natural contaminant chemistry interactions with rock matrix often release undesirable metal concentrations into groundwater. When leached from the rock and minerals, toxic heavy metals can exceed drinking water criterion. Arsenic, cadmium, selenium, and a variety of other heavy metals are documented to have been released at attenuation sites. Metal and ore deposits are often found in trace to significant quantities in many igneous, metamorphic, and intrusive rocks. Sandstones are also known to contain significant concentrations of arsenic and other heavy metals when their depositional basins were derived from granitic and Canadian shield deposits. Significant release of metals is possible if the site-specific contaminants or treatment processes release metals through lowering pH or through other electron donor processes that use metals (for instance, iron and manganese). Aesthetic drinking water problems can occur downgradient of these sites due to increased iron, total dissolved solids, taste, and odor problems.

4.1.6 Volatilization

Depending on their properties, contaminants present in fractured rock may volatilize into the unsaturated fractures or into overburden soils where they can be detected through passive/active soil gas surveys. A soil gas survey can be a valuable tool to detect and characterize the extent and migration pathways for contaminants migrating through fractured rock.

Once contaminants volatilize, transport in fractured bedrock is governed by the fluid flow conditions. Factors such as the depth to groundwater, the nature of fractures, and the characteristics of overburden soils can affect the migration of soil vapors. The nature of fractures within the bedrock and the heterogeneity or anisotropy of overburden soils are important controls on the transport of contaminated vapors, the effects to receptors, and detection in shallow soil gas surveys.

4.2 Contaminant Properties Affecting Fate and Transport

The fate and transport mechanisms that affect the behavior of contaminants in fractured rock depend on the properties of the contaminants. Several examples of how specific contaminant properties affect fate and transport in fractured rock are provided in this section. Table 4-1 includes a list of common contaminants encountered at contaminated fractured rock sites. For each contaminant, physical and chemical properties are identified and the implications for fate and transport in fractured rock are highlighted. Properties that have specific implications for the fate and transport of the contaminants are color-coded in the table. This information can be useful in developing the initial CSM.

Table 4-1. List of common contaminants and characteristics

Click Here to view Table 4-1 in Adobe Acrobat format.

▼*Read more*

Liquid density. Contaminants with a density greater than that of water (such as DNAPL) typically migrate downward into groundwater (sink below the water table) and can also infiltrate bedrock fractures beneath the water table. A detailed discussion of the fate and transport of high-density contaminants is presented in Integrated DNAPL Site Characterization (ITRC 2015b).

Vapor density. Vapor density drives the vertical migration of contaminants. For example, chlorinated solvents generally have a higher vapor density relative to air and migrate at the lower portion of the unsaturated zone that may correspond with fractured rock.

Vapor pressure/Henry's constant. Contaminants with higher vapor pressures/Henry's constants are likelier to partition into the vapor phase. These chemicals are candidates for use of soil gas surveys.

Boiling point. The boiling point for a contaminant can be a significant when selecting remedial strategies. Contaminants such as chlorinated solvents may form a heteroazeotrope with groundwater. A heteroazeotrope is an azeotrope in which the vapor phase coexists with two liquid phases. When two liquids form a heteroazeotrope, their partial pressures are additive, and are effectively boiled out at temperatures below the boiling point of water. This property is relevant, for instance, when evaluating thermal remedial technologies in amenable rock types such as poorly cemented sandstones.

Solubility. Highly soluble contaminants tend to readily partition into groundwater and have the potential to both migrate long distances from the point of release and to enter matrix porosity through matrix diffusion. Contaminants that diffuse into matrix porosity provide a long-term reservoir for dissolved contaminants through gradual back-diffusion. This property can significantly affect remedial actions and should be carefully considered when developing the CSM.

Henry's constant. At a constant temperature, the amount of a gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid

Sorption. Contaminants, such as ammonia, that strongly sorb to soil or rock may be restricted in their vertical migration and may not be encountered in significant concentrations within fractured rock. However, many contaminants with moderate sorption (such as chlorinated solvents) are commonly encountered within bedrock fractures, but also tend to sorb to both soils and the rock matrix. High levels of natural organic matter further retard the vertical and lateral movement of contaminants and are evaluated as they are in unconsolidated media. Typical parameters for the measuring sorption potential include the partitioning coefficient (Kd), the carbon and water partitioning coefficient (Koc), and the octanol water partitioning coefficient, Log Kow.

Reactivity (biogeochemical transformation). Some dissolved contaminants are amenable to biogeochemical transformation because of contact with the rock matrix. For example, many chlorinated solvents (PCE, TCE, DCE) undergo biogeochemical transformation or degradation if the rock matrix is iron-rich.

4.2.1 Contaminant Mixtures (LNAPL and DNAPL)

Highly viscous LNAPLs tend to be restricted in their vertical migration and may not always infiltrate into bedrock fractures. These viscous mixtures of contaminants are seldom encountered within fractured rock settings as separate phase liquid. These mixtures can, however, partition to dissolved or gas phases and contribute to dissolved phase contamination within bedrock fractures. ITRC is updating its guidance on LNAPL characteristics and fate and transport of LNAPL compounds in fractured rock; this update is expected to be published in late 2017 (ITRC 2017).

DNAPL behavior in fractured rock is complex because of the varying degrees of matrix and secondary porosity found in fractured rock. DNAPL flow through fractures may result in dissolution, dissolved-phase advection, sorption and desorption, biochemical transformation, and diffusion into the rock matrix. After migrating vertically through the fracture network, the DNAPL becomes relatively immobile or trapped in small or dead-end fractures because there is no longer a hydraulic gradient or pressure to overcome the pore entry pressures in the rock or displace the water from the fractures. The DNAPL (or ganglia) then begins to dissolve into the water in the fractures and diffuse into the rock matrix. The dissolved-phase constituents migrate with the water flowing through the fractures, forming a plume downgradient of the initial release. As this plume migrates, molecular diffusion occurs within the fractures from the plume to the matrix porosity, where porosity is present.

If a reverse concentration gradient comes into effect, the dissolved-phase contaminants that have diffused into the matrix porosity may then back-diffuse from the same rock matrix into the groundwater traveling within the fractures. This back-diffusion process may sustain elevated concentrations of contaminants in the zones that formerly contained the DNAPL, as well as the previous dissolved-phase plume. The presence of DNAPL constituents presents a potentially persistent reservoir of contaminant mass that can continue to release dissolved contaminants into the groundwater over time. As a result, DNAPLs may persist in the subsurface for several decades or longer, depending on their specific properties. For a more detailed discussion on the fate and transport of DNAPL in fractured rock, see Chapter 3 and Chapter 4 in *Integrated DNAPL Site Characterization and Tools Selection* (ITRC 2015a).

5.8 Lessons Learned

Characterizing and remediating contaminated fractured rock sites is difficult. Common mistakes made at these sites are summarized in Table 5-4. This table is based on field experiences of members of the authoring team regarding fractured rock sites. These common mistakes should also be considered in unconsolidated systems.

Table 5-5 Common mistakes when characterizing a fractured rock system

Common Mistake	Consequence	Remedy
Using an equivalent porous medium (EPM) CSM to investigate a fractured rock system. Scenario: The most upgradient portion of the source area has achieved contaminant reduction goals (PCE, TCE, DCE, and VC) through groundwater extraction after 10 years of operation. Other areas of the source and down gradient areas remain above cleanup criteria. Being unaware of the differences between equivalent porous medium (EPM) and discrete fracture network (DFN) conceptual models and the scale, site conditions, and data quality objectives to which they apply.	Ignores heterogeneous internal structure of bedrock aquifer system and cannot provide a reliable basis for effective delineation or remediation.	Identify a CSM that is appropriate to the site location (fractured sedimentary bedrock, igneous, metamorphic, karst) and refine through appropriate characterization. The EPM model may be sufficient if contamination is limited to shallow weathered bedrock. See Modeling.
Installing monitoring wells at equal, predetermined, or arbitrary depths from surface	Fails to recognize that transmissive fractures are not likely to be oriented parallel to ground surface. Installation of wells at equal depths often results in wells that do not intersect the same water-bearing fracture, frustrating characterization, and delineation efforts. These wells may miss the transmissive fracture zone entirely and may be open to an aquitard unit that is a poor producer of water. The upgradient portion of the source area continues to be pumped from multiple wells at a rate of 70 gpm that appears to no longer be necessary, while other contiguous areas warrant continued groundwater extraction.	The internal structure/architecture of the fracture/aquifer system must be recognized and appropriate tools used to locate transmissive fractures that control groundwater flow at the site. Surface geochemical and geophysical tools can help locate transmissive fractures and, therefore, guide monitoring well installation.

Common Mistake	Consequence	Remedy
Cross-connecting distinct fracture/water-bearing zones	Distinct fracture/water-bearing zones are sometimes cross-connected (particularly when long open boreholes are present, as in production wells) allowing contamination to vertically migrate through the borehole and contaminating deeper portions of the bedrock aquifer system.	Recognize that vertical cross-flows in an open borehole occur wherever transmissive fractures with different heads are penetrated. At DNAPL sites, an outside-in approach (USEPA 1992) should be used that requires that no borehole is drilled into the known or suspected source area until the site-specific hydrostratigraphy and source impacts on groundwater are well understood.
Preparing isoconcentration plume maps as if contamination were in unconsolidated media, without representation of fracture zones	Determine remaining uncertainty in cessation of pumping in this area to enable termination of groundwater extraction while establishing criteria for monitoring the efficacy of terminating extraction in this area. Results in inaccurate and irregular groundwater flow directions. Findings regarding groundwater flow cannot be used to support an accurate delineation of the contaminant plume.	Use only wells intersecting the same fracture/water-bearing zone to determine groundwater flow direction and assess groundwater contamination in that zone. Discrete groundwater level measurements tools such as packers to isolate each fracture to determine their head levels.
Attempted remediation prior to proper characterization of the fractured rock system. Significant data gaps.	Inadequate understanding of the internal structure/architecture of the fracture/aquifer system leads to misdiagnosis of the contamination problem which frustrates and prolongs groundwater remediation efforts. • The potential for back-diffusion from bedrock is not understood. • The contaminant data from the extraction wells may represent a composite sample and concentrations above cleanup criteria may remain in discrete fractures. • The effect of terminating pumping in this area on the overall containment system is not understood.	Proper characterization by an experienced investigator is essential to the design of an effective remediation.
Misinterpretation of vertical hydraulic gradients in a saline fractured rock setting.	Potentially developing a CSM and remedial strategy based on incorrect understanding of the vertical flow gradient.	Adjust water level measurements for salinity/density effects.
Not determining if there is vertical hydraulic flow and if it displays seasonal fluctuation.	Misunderstanding contaminant transport.	Prepare time-series plots of vertical hydraulic gradients. Use transducers to graph relationships over time to further define the system.

Common Mistake	Consequence	Remedy
Only collecting HPFM data under ambient conditions. Unclear or inadequate data collection requirements.	• Potentially misinterpreting the number of discrete samples from fractures • Fracture orientation • Fracture interconnectivity • Hydraulic conditions in a borehole, the absence of pumping	Collect data under both ambient and stressed conditions.
Disregarding historical water level data when preparing groundwater elevation contour figures.	Potentially demonstrating incorrect lateral groundwater flow directions as a result of including anomalous data.	Prepare time series plots showing historical and new water level data for each well for identifying, and evaluating/excluding, anomalous data points.
Incomplete upgradient delineation of contaminants.	May result in treatment or assumed responsibility for contamination from an upgradient/regional plume.	Perform detailed data analysis of the laboratory analytical results to confirm on-site origin.
Not investigating chemical speciation of individual plumes in a fractured rock system.	Potentially delineating the contaminant footprint as one large plume, when in fact there may be several separated plumes.	Illustrate the contaminant ratios for sampled locations and focus on the distribution of “tracer compounds”, which are low concentration constituents that would otherwise go unnoticed.
Incomplete vertical delineation of contamination as a result of only sampling fractures with the highest transmissivity.	Collecting water samples that are biased low (diluted) when there may be fractures with less flow but higher concentrations.	Use geophysical logs or other transmissivity data to select multiple sample depths. Use discrete sampling methodology to determine the most transmissive zones and properly determine contaminant concentrations in each zone. Go to the tools/techniques table for: • Discrete sampling • Orientation • Connectivity
Not recognizing that the water level in an open borehole is often not the water table, but instead is either: 1) the head of a single confined fracture, or 2) the composite head of multiple confined fractures.	Incorrect interpretation of head distribution, gradient and flow.	Use borehole logging to identify transmissive fractures and packers (or equivalent) to quantify discrete fracture heads. Conduct testing to verify if it is a concern, packing and temperature and downhole conductivity monitoring can help to define active gain and loss fractures as well as to map the most dominant flow zones.
Not understanding how/where to sample an open borehole with inflowing and outflowing fractures.	Samples will likely underestimate the maximum concentration in a fracture.	Target transmissive fractures for sampling. Conduct testing to verify concerns; packing and temperature and downhole conductivity monitoring can help to define active gain and loss fractures as well as to map the most dominant flow zones.
Not taking full advantage of outcrops for observing and measuring fractures.	Missed opportunity for Free data. The Structural component of the CSM will be less thorough. May miss vertical or near vertical fractures, which are underrepresented in vertical boreholes.	The right cell should include: Included a qualified field geologist on the team.

Common Mistake	Consequence	Remedy
Drilling deep, open boreholes through contamination; especially in areas with difficult to predict fracturing.	Cross-contaminating previously clean zones.	Assemble an experienced team of a driller/assistant and geologist who communicate and work well together. Stop at the first water-bearing fracture and sample with rapid turnaround (consider an on-site lab). Build flexibility into the plan. Be prepared to grout the hole. If the well is deep, be prepared to drill through a grouted hole. A vertical aquifer sampling program is highly recommended starting from top to bottom with a drilling program that prevents fluid movement between zones during collection of the samples. Casing advancement, grouting, packers, and a combination of techniques may need to be applied to properly characterize contaminant distribution on a newly investigated site
Not accounting for the effect of active supply wells on changing the gradients and contaminant transport.	Mischaracterization of a plume, putting sensitive receptors at risk.	Look beyond the boundaries of the site for pumping wells. Install pressure transducers as necessary to understand induced flow conditions.
Failure to use natural groundwater chemistry parameters to help understand groundwater flow direction.	Missed opportunity for relatively inexpensive data to improve CSM.	Include a person knowledgeable in groundwater geochemistry on the team.
Not effectively or correctly collecting or using geophysical data from boreholes.	Missed opportunity to collect valuable information on: fracture locations and orientations; relations of fractures to stratigraphy; zones of inflows and outflows; borehole conditions such as rugosity and breakouts; and profiles of hydraulic conductivity. If information is improperly used or misinterpreted (generally due to an untrained or inexperienced person working with the data), inconsistencies with other data sets or incorrect input to the CSM could result.	Include professionals who are knowledgeable about borehole geophysical and hydrogeophysical logging and testing in the site characterization team from the beginning.

5 Site Characterization

This chapter presents the components of the characterization process that are unique to fractured rock. Characterizing a fractured rock site follows the Integrated Site Characterization Process described in Figure 4-1 of ITRC's ISC-1, integrated site characterization, guidance (ITRC 2015b). The process is generic and applicable to both fractured rock and unconsolidated media. Most contaminated fractured rock sites have unconsolidated media or weathered material above the bedrock that also require characterization and remediation. Different SMART characterization objectives can be developed for both media using different tools and techniques, but the CSM includes both components. For the unconsolidated media, the ISC-1 guidance and the ITRC DNAPL site strategy guidance (ITRC 2011) describe the unconsolidated component of the site.

Compared to unconsolidated media, intrusive fractured rock investigations can be costly and time consuming; however, these investigations are needed to test assumptions developed during the desktop research and surface investigations. Extensive geologic literature is available, ranging from topographic maps, aerial photographs, satellite imagery, and other geologic and geotechnical investigations to nonpublished reports. To refine the initial site assessment, surface field reconnaissance and outcrop mapping should be completed to project rock type and structures into the subsurface. In addition, subsurface investigations should consider surface geophysical tools to test the assumptions and subsurface projections from the desktop research and surface investigations. Having team members experienced in the geology and hydrology is necessary to select on-site borehole locations, where the information can be gathered to test assumptions made from earlier investigations. Multiple interpretations of the subsurface geology and hydrology should be made and peer-reviewed prior to drilling (Link Appendix C) boreholes. Objectives-based data collection and interpretation are especially important in fractured rock settings, where boreholes are few and expensive.

The Investigation Process

1. Research easily available sources of existing information, such as topographic maps, geologic maps, logs for nearby well, information on nearby bedrock outcrops, and information on other nearby sites.
2. Develop preliminary CSM.
3. Perform appropriate and relevant surface geophysical testing, such as electromagnetic, or VLF.
4. Drill bedrock boreholes targeting surface geophysical anomalies.
5. Conduct appropriate and relevant borehole geophysical logging.
6. Test boreholes for hydrologic characteristics and contaminant distribution (with techniques such as packer testing/packer sampling, heat pulse flow meter, and multiwell aquifer pump testing).
7. Identify significant data gaps.
8. Repeat previous steps as needed to define the horizontal and vertical extent of the groundwater contamination. The CSM should be updated to reflect the results of any newly generated data.

To illustrate the process described in the ISC-1, (ITRC 2015b) Figure 4-1, a hypothetical dissolved VOC contaminated example site is included in Table 5-1. Sections in Chapter 5 will refer to this example to illustrate several points for clarity and application.

Unconsolidated source material has been remediated. A dissolved plume in fractured rock was previously assumed to pose no immediate threat to off-site receptors. A detection has been confirmed in one off-site well, which is known to be screened at a lower elevation than the elevation of the known plume.	
Section 5.1. Review and Refine Existing CSM	Assess if detection identified at lower elevation can be explained with existing CSM, or is plausible within the degree of uncertainty of the existing CSM
Section 5.2. Define the Problem, Define Characterization Objective	Problem: The vertical contaminant distribution and/or rate of plume expansion/migration are inadequately understood. Objective: Delineate the vertical and lateral extent of the plume, then develop strategies for the protection of deep off-site receptors.

Unconsolidated source material has been remediated. A dissolved plume in fractured rock was previously assumed to pose no immediate threat to off-site receptors. A detection has been confirmed in one off-site well, which is known to be screened at a lower elevation than the elevation of the known plume.	
Section 5.3. Identify Significant Data Gaps	• maximum depth of contamination exceeding criteria • maximum lateral distance (from the source) of contamination exceeding criteria • direction in which the deepest/farthest contamination is flowing • rate at which the deepest and farthest contamination is flowing
Section 5.4. Define Data Collection Objectives and Design Data Collection Process	• discrete samples from deep fractures • orientation of deep fractures • connectivity among deep fractures • gradient within interconnected, deep fractures • transmissivities within interconnected, deep fractures
Section 5.5. Select Tools/Techniques	• Use borehole televiewer, caliper, temperature and HPFM logs to identify potential water-bearing fractures at each location. • Use borehole televiewer log to assess fracture orientation at each location • Use borehole packer sampling to collect groundwater samples from discrete water-bearing fractures and provide vertical profile of contamination and of hydraulic conductivity of fractures at individual borehole. • Measure head changes in adjacent wells during drilling and packer testing to assess fracture connectivity. • Conduct transmissivity profiling of boreholes. • Install wells to monitor deep water-bearing fractures identified. • Measure water level in wells to assess horizontal and vertical gradients. • Perform tracer testing to assess fracture connectivity and groundwater velocity. • Perform pumping tests to evaluate transmissivity, fracture connectivity, and anisotropy.
Section 5.6. Develop and Implement Work Plan	Prepare and implement a work plan for characterization activities.
Section 5.7. Manage, Interpret, and Present Data	Manage and interpret data to refine CSM and communicate findings and CSM. Refine CSM and assess if characterization objective is met or significant data gaps remain (return to steps at beginning of this table).

Many sites have existing information from previous site investigations. Most sites will have an existing CSM and this model should serve as the beginning of any investigation.

5.1 Review and Refine Existing CSM

The CSM is the primary vehicle used to organize and communicate technical information about site characteristics. As outlined in *Incremental Sampling Methodology* (ITRC 2012a), CSMs are essential elements of the systematic planning process. These models represent the relationship between contaminant sources and receptors by incorporating potential or actual migration and exposure pathways. They also provide a framework to collect and manage site data necessary to support project management decisions.

The CSM encompasses all significant components of contaminant fate and transport at a site. While this guidance focuses on fractured rock, an unconsolidated portion often exists and should be included in the same CSM. Guidance for preparing a CSM for unconsolidated environments is included in the IDSS-1 document (ITRC 2011). Contaminant transport often affects both unconsolidated and consolidated geology as well as different hydrogeologic flow regimes. Additionally, multiple separate or comingled contaminant plumes may be present. These individual components form a CSM only when they are combined into one comprehensive system that characterizes the relevant site conditions.

The CSM should reflect the best interpretation of available information at any point in time. Consequently, it is a living document that should be updated continuously as new data are collected at any stage of the investigation and remediation. If new data are inconsistent with the existing CSM, the data and CSM should be further evaluated and the CSM revised as needed.

To help visualize a basic CSM, the 21-Compartment Model can be used to illustrate several concepts related to the fate and transport of contaminants in fractured bedrock settings. Using this model with site-specific information offers insight into the relationships among contaminant phases, bedrock geology, and bedrock hydrology. The results of the 21-Compartment Model evaluation are well-suited for developing or refining the CSM. For example, in Table 5-1, compartments in the 21-Compartment Model can be blocked out as the location and movement of the dissolved VOC mass. The compartments dealing with the vapor phase may still be relevant, however, depending on the site characteristics and potential receptors.

Unfortunately, some CSMs omit critical characteristics that greatly influence the quality of a CSM in fractured rock. Section 1.2 describes these characteristics. Terrane analysis presents key elements that should be evaluated, from a physiographic province scale to finer site scale, to compile an initial CSM:

- regional physical setting (such as physiographic province)
- structural geology and tectonic setting
- lithology and stratigraphy/mechanical stratigraphy
- predicted anisotropy and heterogeneity

Many of these site characteristics are specific to fractured rock settings, and available literature and data should be carefully reviewed before undertaking a characterization study.

Likewise, fluid flow in fractured rock is influenced by the following:

- matrix (primary porosity) flow, which varies according to the lithology and micro-structures of the rock
- fracture (secondary porosity) flow, which is influence by the characteristics of the fractures

Figure 3-1 illustrates the degree of influence the various characteristics lend to a macro-, meso-, and micro-scale flow regime.

Finally, the chemical characteristics affect the fate and transport of contaminants and contaminant mixtures. These characteristics, which are often available in the literature, are essential for understanding the fate of contaminants in any setting, including fractured rock.

A range of tools and techniques for resolution of critical physical, hydrologic and chemical relationships are available. Some of these tools and techniques are specialized to address fractured rock settings, and others are commonly used in both fractured rock and unconsolidated settings. Some collect information from boreholes, and some collect information from the surface, but most importantly note that desktops surveys of existing regional and local information can often describe the site geologically, hydrologically, and chemically.

5.2 Define the Problem

> *"A problem well stated is a problem half solved."*
>
> -Charles F. Kettering, 1876-1958, Head of Research, General Motors

The value of an effective problem statement cannot be stressed enough for fractured rock settings. All other factors being equal (including contaminants, concentrations, plume size, mass flux), investigations in fractured rock generally have greater uncertainty—requiring greater investments of time and money to reduce that uncertainty—than those in unconsolidated materials. To manage these risks, the project should begin with a concise problem statement.

The problem statement for a hydraulic investigation of a fractured rock site has components that differ from those for unconsolidated materials because of the unique attributes of fractured rock. Table 5-1 includes an example problem statement:

The vertical contaminant distribution and rate of plume expansion or migration are inadequately understood.

This example is only one of several potential problem statements that could be written for this hypothetical site. This problem statement leads to an initial characterization objective: *delineation of the vertical and lateral extent of the plume, enabling the development of strategies for the protection of off-site receptors*. This objective is followed by the identification of significant data gaps, resulting in one or more specific data collection objectives. Contamination may be found flowing at different depths, at different rates, and in different directions.

Information from past activities at a site is sometimes available. If site information is not available, consider accessing available data and information from nearby and hydrogeologically similar sites. Attributes such as rock type, fracture size, location and continuity, and geologic structure are usually unknown, thus initial site investigations refine the problem statement and describe clear characterization objectives. An additional example of problem statements are found in the case example in Section 6.5.

5.3 Identify Significant Data Gaps

Data gaps in CSMs occur throughout the characterization process. Data gaps are normal in CSMs because the models rely on working hypotheses in various phases of completion and on incomplete information. To maximize efficiency and cost-effectiveness, consider the influence of physical, hydrologic, and chemical characteristics on fate and transport. At each stage, investigators must identify significant data gaps, as well as which data needs should be addressed (data collection objectives) and which can be ignored.

Table 5-1 notes several examples of data gaps:

- vertical and horizontal extent of contamination
- the direction of contaminant movement
- the rate of contaminant movement

Each of these data gaps can easily be transformed into one or more specific characterization objectives. For example, the second data gap becomes the objective: *determine the direction of contaminant movement.* The resulting data collection objective to resolve this data gap might be to use borings to provide site-specific data on VOC concentrations at various depths. Locations of these borings can be determined with the help of the desktop evaluation. While all data gaps are assessed when confirming or refuting the CSM hypotheses, only significant data gaps should be considered for further investigation. The data gap in this example is significant because any deep migration of VOCs threatens the existing water supply wells.

One way to identify data gaps is using the 21-Compartment Model, completed during assessment of the initial CSM. After supplying the known information, partially filled or empty compartments may identify significant data gaps.

5.4 Define Data Collection Objectives and Design Data Collection Process

Once the data gaps are identified, investigators can establish specific data collection objectives and design the data collection process. Data collection objectives are used to determine specific data needs and to select tools and techniques to be used in the investigation. This section describes data collection objectives common to many fractured rock sites, as well as the design of the data collection process and key factors that should be considered in the characterization planning.

5.4.1 Establish Data Collection Objectives

Once the significant data gaps are identified, specific data collection objectives can be established. A more detailed discussion on data collection objectives is included in *Integrated DNAPL Site Strategy* (ITRC 2011) and *Integrated DNAPL Site Characterization and Tool Selection* (ITRC 2015b). The data collection objectives depend on the purpose and stage of the characterization. For example, the data collection objectives developed as part of a remedial investigation may differ from those developed for assessing the effectiveness of remedial alternatives.

Data collection objectives should be clear, focused, and specific. Objectives should account for factors such as fracture orientation, spacing and aperture, hydraulic head, and flow velocity. These characteristics define the type of data needed, the data density and spatial resolution, and measurement and analytical resolution. As these objectives become more focused, they help to determine the type of data quality (quantitative, semiquantitative, or qualitative) required to meet the data collection objective and thus the appropriate investigative tools.

The fourth significant data gap noted in Table 5-1 is: *the rate at which the deepest and farthest contamination is moving*. Based outcrop mapping and available structural maps, a number of fractures, or other planar features, are oriented toward down gradient water supply wells. However, VOC data collected from a deep-water supply well indicate contamination is sidegradient to the assumed flow direction. The data collection objectives in this situation may be as follows:

1. Document the orientation of fractures sets in the subsurface to the base of the deepest screened water supply well.
2. Define the interconnectivity of fractures.
3. Measure the flow velocities in discrete borehole intervals.
4. Calculate the groundwater gradient between the source area and water supply wells.

Another example of a significant data gap, with corresponding specific characterization and data collection objectives, is presented below:

Significant Data Gap: The vertical and lateral extent of dissolved phase contamination is unknown.

Characterization Objective: Determine the lateral and vertical extent of dissolved phase VOCs.

Data Collection Objective: Gather data, including fracture location, orientation, connectivity, and VOC concentration in areas beneath the source and between the source and the water supply wells.

The data characterization process is shown in Figure 4-1 of the DNAPL site characterization guidance (ITRC 2015b).

5.4.2 Design Data Collection Process

After establishing the data collection objectives, the next step is to design the data collection process. Designing or developing this process begins before the selection of investigation tools, and is an integral and iterative process within the selection of investigation tools. The design includes sequencing and planning characterization activities. Additionally, the process is optimized to ensure representative data, identify cost-effective approaches, and prevent the spread of contamination during the investigation activities. The sequencing and approach developed from this process should be incorporated into the project work plan.

In general, the data collection process should begin with available data and data obtained through nonintrusive evaluations. These findings can then be used to plan intrusive measures (such as boreholes) if needed. Thus, the initial steps should include the components of the terrane analysis that use available resources and techniques, such as: topographic and geologic maps, light detection and ranging imagery (LiDAR), and aerial photography, to conduct activities such as lineament analyses and initial cross-sections construction. Minimally intrusive or nonintrusive field activities should follow, including surface reconnaissance techniques (such as mapping, outcrop analyses, and measurements) and surface geophysical surveys (such as ground penetrating radar and electrical resistivity).

These results may indicate the need for intrusive methods. For fractured rock characterization, subsurface data are collected using existing boreholes and wells, or a borehole or well installation program to supplement the existing data. The number and locations of data points may be selected subjectively at first, but several approaches can bring objectivity to the selection process. In selecting subsurface data collection locations, first consider how the general structure, or *fabric,* of the terrane and fracture orientations may affect groundwater flow and contaminant migration.

An example of selecting fractured rock (Appendix C) locations is presented in Figure 5-1. After reviewing available site information, potential source area locations may be mapped and initial investigative borehole locations can be selected. This decision may differ between boreholes drilled in unconsolidated deposits versus those that may need to be drilled in fractured rock, as illustrated. The general regional bedrock structural fabric (strike and dip) is considered, and the array of bedrock drilling locations can be rotated toward the structural fabric orientation, with the amount of rotation determined by the dip angle of the fabric. Generally, there is no rotation with horizontal or subhorizontal dip, and more rotation with steeper dips. In general, the middle of the downgradient monitoring well array should be within the acute angle defined by the estimated hydraulic gradient direction and a line drawn parallel to the dipping regional bedrock structural fabric through the interpreted source.

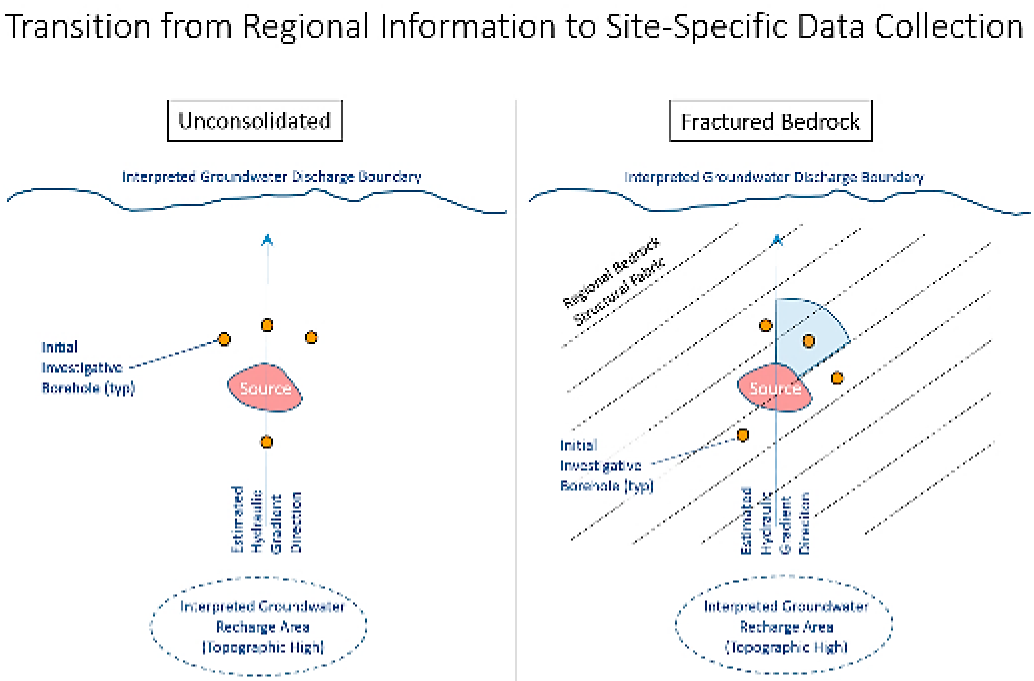


Figure 5-1. Selection of Initial Fractured rock Drilling Locations

The number and locations of data collection points needed cannot be predicted. Investigators should consider the number, type and amount of data required as part of the next field investigation to further refine the CSM. After several iterations of this process of data collection and evaluation, the number and locations of data become adequate to support informed decision-making, the significant data gaps are resolved, and the CSM is refined. The most recently collected data might not materially change the CSM, which indicates that the CSM may be adequate for future decision making. Judgments regarding data adequacy in terms of number and location are usually qualitative, may involve many stakeholders, and depend on the characterization objectives for the given stage of the project.

The factors listed below should be considered when designing a data collection process, selecting characterization tools, and developing the overall approach and sequencing of the process.

Using existing wells or boreholes with long open intervals ▼*Read more*

Early in the development of the subsurface investigation program, consider if the site already has existing wells (such as production wells or old monitoring wells) or boreholes, which may be used or retrofitted as data collection wells for future site characterization and monitoring. Note that wells with long open or screened intervals could detrimentally affect site conditions. Data collected from these wells may have limited value without further borehole characterization or modification for multizone isolation (for instance, installing packer strings to preserve the opportunity for future zone-specific vertical profiling, multizone testing, or interval-specific remediation). Production wells in bedrock often are drilled to whatever terminal depth is required to achieve the desired well yield—hundreds of feet in some cases—and commonly are completed with long, open boreholes. Preexisting supply wells or boreholes with long open intervals may have exacerbated subsurface contamination and may still affect groundwater by allowing cross-contamination between discrete water-bearing zones that would otherwise have limited hydraulic interconnection. Hydraulic head data and groundwater samples collected from wells with long open intervals are of limited value for characterization because the resulting information is a composite of each interval and cannot be ascribed to any particular depth within the formation.

Preexisting wells or boreholes with long open intervals may need to be grouted and decommissioned or converted to monitoring points early in the site characterization process. Contaminants may have been mobilized into former pumping wells and in some cases, deep bedrock production wells that have been repurposed for waste disposal. These wells may be key locations for site characterization and monitoring and should be strongly considered for retrofitting as monitoring points. Often, the diameters of supply wells are large enough to fit multiple monitoring wells with screens and sand packs at multiple depths, separated by appropriate borehole seal materials (such as bentonite or grout). Alternatively, multiport wells/sampling devices can be installed at specified depth intervals. Prior to selecting permanent monitoring depths, however, the borehole should be characterized using downhole methods, depth-discrete sampling, or both to identify predominant flow zones and their specific chemical signatures or fluxes interval. This evaluation should include a borehole geophysical logging program.

Strategies for borehole/well installation programs ▼*Read more*

General factors to consider when designing a drilling program in fractured rock include:

- Bedrock evaluations typically require more money and time per data element than investigations performed in unconsolidated media. Consequently, using a conventional phased approach or an adaptive approach, especially when the CSM is uncertain (such as in the early stage of an investigation, in an area with little prior characterization, or in structurally complex systems) can help optimize the characterization efforts.
- Data collected during the drilling of a borehole (with a permanent well or monitoring device) are often as important as data collected from a completed monitoring well. For example, in situ fracture orientation data, which are crucial for evaluating likely fluid-flow directions, must be collected from boreholes before installing monitoring wells and other monitoring systems.
- The basis for a potential depth limit for the investigation should be defined for each phase of work; this basis may change between phases of work as the CSM is developed. A depth limit may be set based on the current understanding of bedrock stratigraphy (for example, encountering a certain recognized regional aquitard) or data collected while drilling (for example, vertical profiling of contaminant concentrations in screening-level groundwater samples, hydraulic conductivity, or both).

See Appendix C for more specific guidelines for drilling programs and drilling techniques.

Precautions and management of long open boreholes during a drilling program ▼*Read more*

Long open intervals in bedrock provide ambiguous data and can act as conduits for cross-contamination between water-bearing zones. According to Sterling (Sterling 2005):

Rock-core analyses, combined with the other types of borehole information, show that nearly all of this deep contamination was due to the lingering effects of the downward flow of dissolved TCE from shallower depths during the few days of open-hole conditions that existed prior to installation of the multilevel system.

This study concluded that the lingering impacts of borehole short-circuiting can be particularly persistent in rocks with significant matrix porosity, due to matrix-diffusion effects. Thus, it is important to plan, collect, and interpret data quickly during the drilling process. Working quickly allows monitoring intervals to be selected rapidly and the borehole completed or packed and isolated as quickly as practicable after drilling.

Some approaches to reduce cross-contamination during borehole advancement include:

- Use fresh, potable water to flush rock cuttings, collecting the water and disposing of it, (after treatment if needed), rather than recirculating the water. Similarly, using air-rotary or air-hammer drilling can be considered for situations when it is not necessary to collect rock core.
- Install temporary packers (such as inflatable packers or K-packers) or FLUTe liner in boreholes when not drilling.
- Drill with mud to form a mud cake on the borehole wall to limit exfiltration of fluids from the borehole into formation. Be careful to avoid plugging or reducing permeability in fractures intersecting the borehole; synthetic drilling muds that can be decomposed after drilling may be appropriate here.
- Drill using the dual-wall reverse-circulation drilling technique. In this technique, the drilling fluid (water, drilling mud, or air) is circulated downward between the outer and inner casings of the drill string. The drill cuttings and the drilling fluid enter openings on the drill bit, which is attached to the inner casing (the drilling rods) and circulate upward within the inner casing to the surface. The outer casing, which advances as drilling progresses, can help reduce the potential for cross-contamination within the borehole.
- Install intermediate casings during borehole advancement to isolate the shallower, potentially impacted intervals from the borehole prior to drilling deeper. Multiple casings can be installed at one location, if necessary, although the initial borehole diameter limits the number of intermediate casings that can be installed.

DNAPL contingency planning ▼*Read more*

DNAPL that is pulled down through incomplete boreholes can contaminate deeper, previously clean bedrock zones. When drilling at a site that may have DNAPL in the subsurface, have a plan to recognize DNAPL and avoid drilling deeper if it is encountered. Watch drilling fluids, rock cuttings, and core samples for an oily appearance or sheen and monitor VOC concentrations with a photoionization detector (PID) or similar instrument. If an oily appearance or sheen is observed, or there is a substantial increase in VOC readings, stop drilling and evaluate whether pooled DNAPL (which is potentially mobile) is present. Check the bottom of the borehole for pooled DNAPL using an interface probe or bottom-loading bailer. If pooled DNAPL is not encountered and if the drilling method uses recirculated drilling fluids (such as mud rotary drilling), the drilling fluids should be replaced with clean water before drilling deeper. Replacing the drilling fluids reduces the potential for cross-contamination and makes it easier to see a new sheen encountered at a deeper interval.

Accumulated DNAPL in the bottom of the borehole, however, indicates pooled DNAPL. If DNAPL has accumulated, remove it using a bottom-loading bailer or pump. Then, grout the borehole or quickly install a DNAPL monitoring well equipped with a sump below the screen. Fill the annular space surrounding the sump with grout.

Sometimes, a discrete fracture or interval of fractures can be identified in the borehole where the DNAPL was encountered. For example, if a rock core indicates the rock is generally unfractured, competent, and has little matrix porosity, yet there is a discrete fracture or zone of fractures within the core that indicates DNAPL presence (such as visible NAPL, sheen, staining, elevated PID readings), this fracture may be the NAPL-bearing fracture. If there is a sufficiently long interval (at least several feet) of competent, unfractured rock with low matrix porosity below this fracture, an intermediate casing can be set in the borehole to isolate the DNAPL-bearing fracture from the borehole, and thus allow deeper drilling. If an intermediate casing is set, after the grout is cured the drilling fluid should be replaced and the casing should be flushed with clean water. The water flushed from the borehole should be observed and monitored for indications of residual DNAPL. When the borehole is advanced again, the same DNAPL monitoring should continue.

In addition to the contingency planning at individual drilling locations, the sequence of borehole locations can be used to reduce the potential for cross-contamination. If practical, first assess the bedrock system at locations that are expected to be uncontaminated or contain only low levels of contamination before drilling in highly contaminated areas. Findings from these less-contaminated areas will improve planning to minimize cross-contamination when drilling in more contaminated areas (working from the outside to the inside, clean to dirty).

Data collection during borehole advancement ▼*Read more*

The following data should be collected as a borehole is being advanced, if applicable to the selected drilling methodology:

- drilling rates (minutes per foot, and changes in rates), which indicate the general competency of the bedrock
- water production (air rotary or mud/water rotary drilling) or loss (mud/water rotary drilling), which indicates the

approximate first encounter of relatively permeable zones
- rock quality designation (RQD), which is semiquantitative, measures the competency of the rock, and is inversely related to the degree of fracturing.

RQD (each core run) = [sum of lengths of rock pieces 4 inches (10 cm) or longer]

[total core run length]

The lengths of rock pieces are measured along the centerline of the core sample. Rock quality can then be described as follows:

Table 5-2. Rock quality designations (QJEG 2007)

RQD	Rock Mass Quality
<25%	completely weathered rock
25-50%	weathered rock
50-75%	moderately weathered rock
75-90%	Hard rock
90-100%	fresh rock

▼*Read more*

- indications of contamination (visual, olfactory, PID) in drilling fluid, rock cuttings, or rock core samples
- core sample inspection data: lithology, stratigraphy, fracture orientations, identification of fracture sets, indications of weathering/staining from groundwater flow, fracture infilling, indications of contamination, and other indications as appropriate

- rock core sampling for laboratory analysis of rock matrix parameters (such as porosity, bulk density, total organic carbon, and contaminant concentrations)
- cuttings: lithology, indications of contamination
- water levels in adjacent wells, preferably through continuous monitoring using data logging pressure transducers, which provide inexpensive data regarding connectivity between existing and new boreholes
- single-packer testing of the newest drilled borehole interval, for hydraulic conductivity profiling and, if water is extracted rather than injected, collection of screening-level groundwater samples

Data collection after borehole drilling, prior to well or casing installation ▼*Read more*

The following data should be collected once borehole drilling is complete, but before a well is installed in the borehole or before installing an intermediate casing across an interval of a borehole:

- dual-packer (straddle packer) testing of borehole intervals, for hydraulic conductivity profiling of discrete borehole intervals and, if water is extracted rather than injected, collection of screening-level groundwater samples
- borehole geophysics, particularly optical or acoustic televiewer for measurement of the orientations and spacing of in situ bedrock fractures, and other borehole geophysical tools/methods, to log lithologic changes and other rock properties; see Tools Selection Worksheet and USGS "Geophysical Toolbox" (Day-Lewis 2016)
- heat-pulse flowmeter, with and without in-well pumping, to identify transmissive fractures and potential in-flow and out-flow zones intervals
- transmissivity profiling to identify transmissive fractures and borehole intervals
- NAPL/FACT FLUTe, to identify specific depth intervals of NAPL or dissolved phase concentrations possibly indicative of NAPL in contact with the borehole wall
- borehole tracer tests

Borehole Completion ▼*Read more*

Considering the data collection objectives, use the data collected from each borehole to select target intervals for monitoring well completion (screen or open-rock), or multiple target intervals for a multilevel monitoring system. If the monitoring system will not be installed soon after borehole drilling and testing, minimize the potential for cross-contamination from the borehole using temporary packers, a FLUTe® liner, or other appropriate methods.

Characterization of uppermost bedrock ▼*Read more*

Often, the uppermost bedrock (positioned either directly below unconsolidated deposits or exposed at the ground surface) may be more weathered and fractured, or may contain fractures of larger aperture than more competent, underlying rock. As a result, the uppermost rock may have significantly different hydrogeologic characteristics and broader contaminant distribution than the deeper bedrock. In some cases, much of the contaminant mass resides in the upper weathered bedrock interval.

A well-designed bedrock characterization program accounts for this upper contaminant mass and includes provisions to characterize this interval. In some jurisdictions, well drilling regulations can require that as much as 10 to 20 feet of the upper bedrock that underlies the unconsolidated deposits be cased off before advancing the borehole deeper into bedrock to prevent cross-contamination. This potentially significant interval may not have been characterized at some sites during the initial phases of an investigation. Examples of activities to assess the upper bedrock before it is permanently cased off include:

- setting a temporary casing to isolate the overburden prior to drilling into the interval and then coring the interval for lithologic, structural, or chemical assessments
- conducting short-term pumping yield tests, slug tests, or other hydraulic assessments
- collecting groundwater samples from the interval

Some jurisdictions that require the upper bedrock to be cased off also may grant variances to the regulations to permit assessment of the upper rock. This process requires planning and coordination with the appropriate regulators.

Characterization activities using wells or multilevel monitoring systems– types of data collection activities ▼*Read more*

Once monitoring wells or multilevel monitoring systems are installed, multiple locations can be characterized. Some examples of data collection activities for finished wells or multilevel monitoring systems include the following:

- Water level measurements provide hydraulic head data in three dimensions to assess hydraulic gradients, which can be used to estimate groundwater flow directions and flow rates. Use caution, however, in estimating flow directions in bedrock based solely on hydraulic gradient direction, because fractured bedrock systems are often anisotropic with respect to the hydraulic conductivity. In addition, hydraulically active features, such as fractures, from separate boreholes may not be continuous or connected. Thus, there is little value in attempting to demonstrate a flow relationship based on their head differentials. Continuous monitoring of water levels with data-logging pressure transducers can be used to determine the degree of hydraulic connectivity within and between water-bearing fracture zones.
- Groundwater samples are collected and analyzed for constituents of concern to assess the nature and extent of dissolved phase chemicals in groundwater. Because chemical constituents act as long-term tracers, these data can also be used to help assess the continuity of fractures and improve the understanding of groundwater flow directions in the fracture system. Data for naturally occurring major ions (calcium, sodium, magnesium, potassium, bicarbonate, carbonate, chloride, and sulfate) and total dissolved solids (TDS) can be used to fingerprint the natural chemistry of groundwater to assess the degree of hydraulic connection or isolation of groundwater in different fracture horizons. It is also common for a source area to have its own unique geochemical fingerprint that is easily identified and different from the naturally occurring aquifer fingerprint. These source area parameters can be contiguous with the contaminants and are generally found at a greater distance from the last occurrence of contaminants.
- Pumping tests can be used to characterize aspects of a fractured rock system such as hydraulic conductivity (which can be used to calculate fracture apertures, continuity of fractures, connectivity of fractures, anisotropy, and hydrogeologic properties of water-bearing zones. Down hole cameras can also show immediate changes when pumping stress occurs and can identify which zones are connected to the supply wells.
- Tracer tests can be used to assess fracture connectivity, groundwater velocity, and fracture porosity. In addition, if the tracer test is conducted to design an in situ groundwater treatment approach, a reactive treatment reagent may be injected together with a conservative, nonreactive tracer. Using the proportions of the reactive

and nonreactive tracers relative to their injected concentrations detected over time at nearby observation wells, the half-life of the reactive tracer can be characterized and used to support the design the spacing between injection wells.

5.5 Select Investigation Tools

Once the CSM is developed, data gaps are identified, and data collection planning is complete, the appropriate investigation tools and techniques can be selected. Often, several tools could be used to collect data for a specific data collection objective. Selecting the optimum tool relies on several factors to establish that it is appropriate for the task, including:

- availability and cost of the tool
- reliability of the tool
- familiarity with the tool
- required expertise to use the tool
- acceptability of data to stakeholders

Selection and proper use of any investigative tool is fundamental to a successful project and is ultimately the responsibility of the project team.

This guidance provides an interactive which offers over 100 investigation tools that can be used to collect the data needed to satisfy the data collection objectives. The Tool Selection Worksheet offers a rapid method of identifying the appropriate tools and information for collecting geologic, hydrologic, and chemical data. A well-designed characterization objective can be translated into a logical sequence of dropdown menus in the worksheet that narrows the list of tools to those that can be used to collect the needed data. Once a shortlist of tools has been identified, the project team can incorporate the tools as appropriate into an investigation work plan for review and approval by regulators and stakeholders.

5.5.1 Overview of the Tools Selection Worksheet

The Tools Selection Worksheet is organized in a spreadsheet format. The left column incorporates a comprehensive list of tools and the rows are subdivided by categories of tools. Parameters are listed across the top of the columns and are also separated into three categories: Geology, Hydrogeology, and Chemistry. The shaded boxes indicate that the tool listed in that row can be used to collect information about the parameter in that column. For example, packer testing can be used to collect data to calculate hydraulic conductivity. The worksheet also lists tools that are effective in unconsolidated, bedrock, saturated, or unsaturated environments, and whether the tools can be used to provide quantitative, semiquantitative, or qualitative data. Although many of the tools can provide data in all subsurface conditions, some are limited. For example, some tools cannot be used in screened or cased holes or in unsaturated conditions, and others may be able to penetrate relatively shallow depths in unconsolidated material but cannot penetrate bedrock and require a borehole.

In the Tools Selection Worksheet, each tool name links to additional information such as descriptions and applicability of the tool, advantages and limitations, data quality capability, and challenges that may be encountered when using the tool. Additional information is provided in the citations at the end of each technology description. These citations are linked to the full reference information, and each parameter in the Worksheet links to a definition of that parameter.

5.5.2 Using the Tools Selection Worksheet

Figure 5-2 presents a screenshot of the dropdown menus in the worksheet that define the search functions for the tools selection. Using a well-formulated data collection objective, tools selection can be made from the dropdown menus and then *Search* selected to generate a shortlist of the appropriate tools. The five menus are used in a stepwise process as follows:

1. **Media Type:** What is the nature of media being investigated, and what category of data is being collected (geologic, hydraulic, or chemical)?
2. **Media Parameter:** What parameter is of interest?
3. **Subsurface Media:** Is media being investigated unconsolidated porous materials or bedrock?
4. **Media Zone:** Is the target zone saturated or unsaturated?
5. **Data Quality:** What is the data quality objective: quantitative, semiquantitative, or qualitative?

Clicking the search button after answering these questions with the dropdown menus will populate a new tab in the worksheet with a subset of tools to be further narrowed down after reviewing the information linked from the name of the tool. The worksheet allows multiple searches, each populating a separate tab at the bottom.

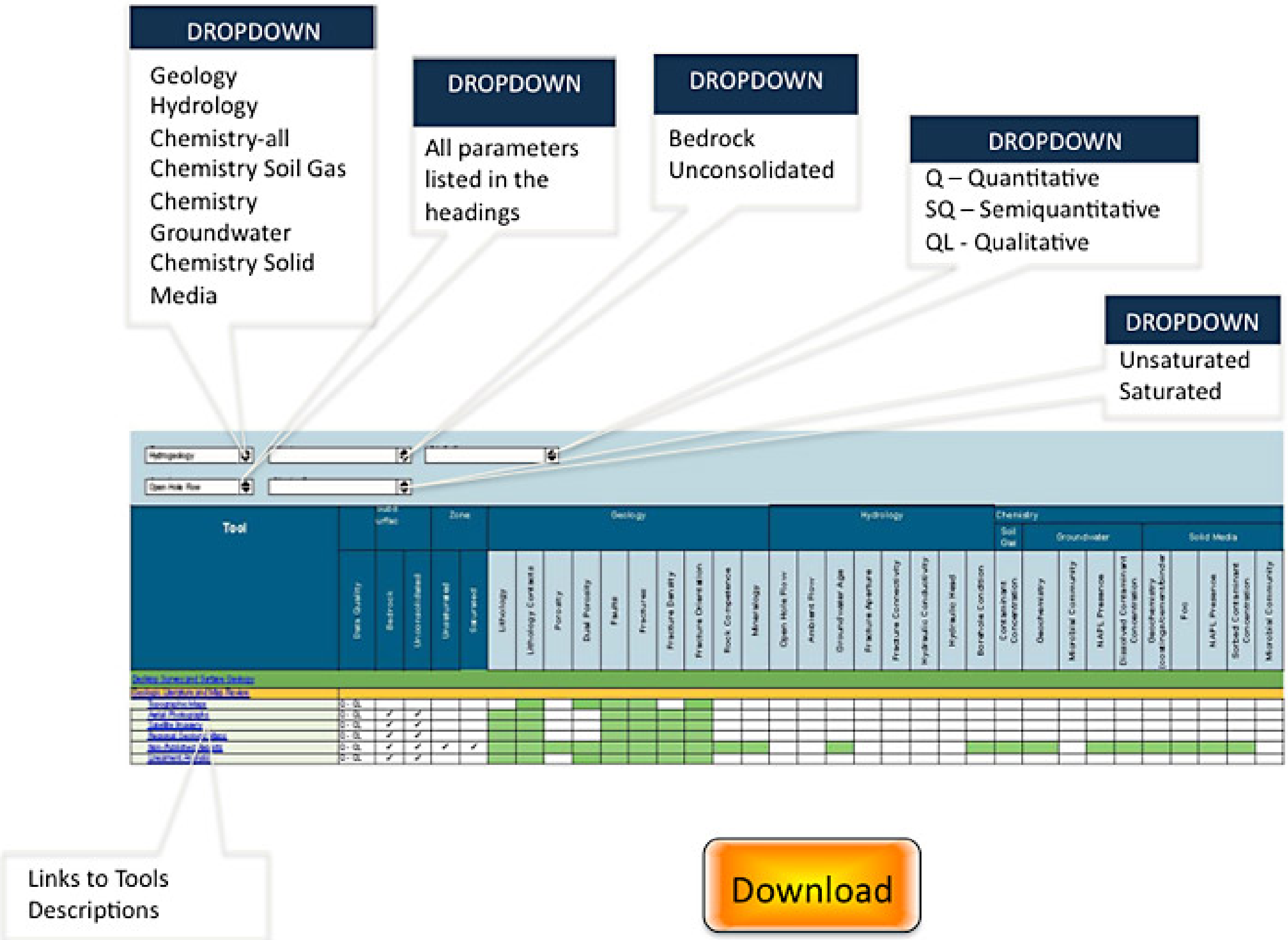


Figure 5-2. Tool Selection Worksheet.

The tools descriptions should be reviewed to assess the best options for a particular site characterization or remediation. The extensive references make researching specific tools easier and quicker because some of the tools, originally classified as applicable, may be eliminated based on site conditions, access, cost, availability, deployment challenges, or DQOs described in the literature. Note that this Tool Selection Worksheet does not select individual tools, but rather narrows the choice of tools depending on the data needs and investigation plan. The worksheet may return multiple tools as options, so searches may need to be refined to reduce the number of applicable tools. Ultimately, the project team selects the appropriate tools from the shortlist.

5.6 Develop and Implement Work Plan

The purpose of this step in the fractured rock site characterization process is twofold:

1. Assemble and integrate the objectives that have been formulated to fill the data gaps in the CSM into an executable work plan. This work plan can be accepted by stakeholders and used to guide the data collection and analysis process.
2. Implement the work plan and evaluate the results so that the CSM can be updated and evaluated for remaining data gaps.

5.6.1 Develop Project Work Plan

Developing a project work plan is not necessarily difficult. Depending on the scope of the characterization activities and regulatory requirements, the work plan can be a focused and streamlined document that can be prepared relatively quickly. A typical fractured bedrock characterization work plan should include the following criteria:

- Emphasize characterization and data collection objectives.
- Present a data collection process.
- Include the tools selected.
- Discuss the procedures/software/models that will be used for data evaluation and interpretation.

An well-designed work plan is flexible enough to allow changes to the characterization approach based on real-time results obtained during the investigation. A dynamic field approach using TRIAD principles, to the extent practical, is effective at fractured rock sites. This approach may require frequent (up to daily) calls or data uploads between the field team and project stakeholders. Frequent communication allows the team to review field activities and data, make decisions based on real-time data, and discuss next steps for efficiently completing the characterization. The work plan outlines the process for documenting field changes or adjustments during the site investigation. In addition, the work plan outlines the process for handling substantial changes to the investigation plan—beyond what is considered a standard field change.

The work plan includes sufficient information about selected tools to describe how each tool will be used, the investigation locations, types of data and to be generated, DQOs, data management, and data interpretation that will be performed. If the selected tools generate real-time data or nonstandard data (such as data beyond traditional analyte concentrations, or data generated by profiling or logging tools), the work plan describes how the data will be obtained and communicated to the project team. Also, the work plan describes how the data will be managed and stored along with other data used in the overall CSM.

5.6.2 Implement the Site Investigation

Once the work plan has been developed and approved, the next step is to implement the site investigation. Depending on the tools that are selected for the investigation, portions of this step may run concurrent to the initial phases of data management, interpretation, and presentation. If real-time or near-real-time data are being generated during the investigation, then these results can be evaluated as they are generated to help guide further data collection activities.

This guidance describes the overall process and framework for site characterization, rather than details on specific techniques or approaches for implementing field investigations. Sites should be investigated according to generally accepted principles and procedures for environmental fieldwork and should rely on the expertise of the project team. Any subcontractors or vendors that are used to deploy the selected tools should follow specific operating procedures and protocols.

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.

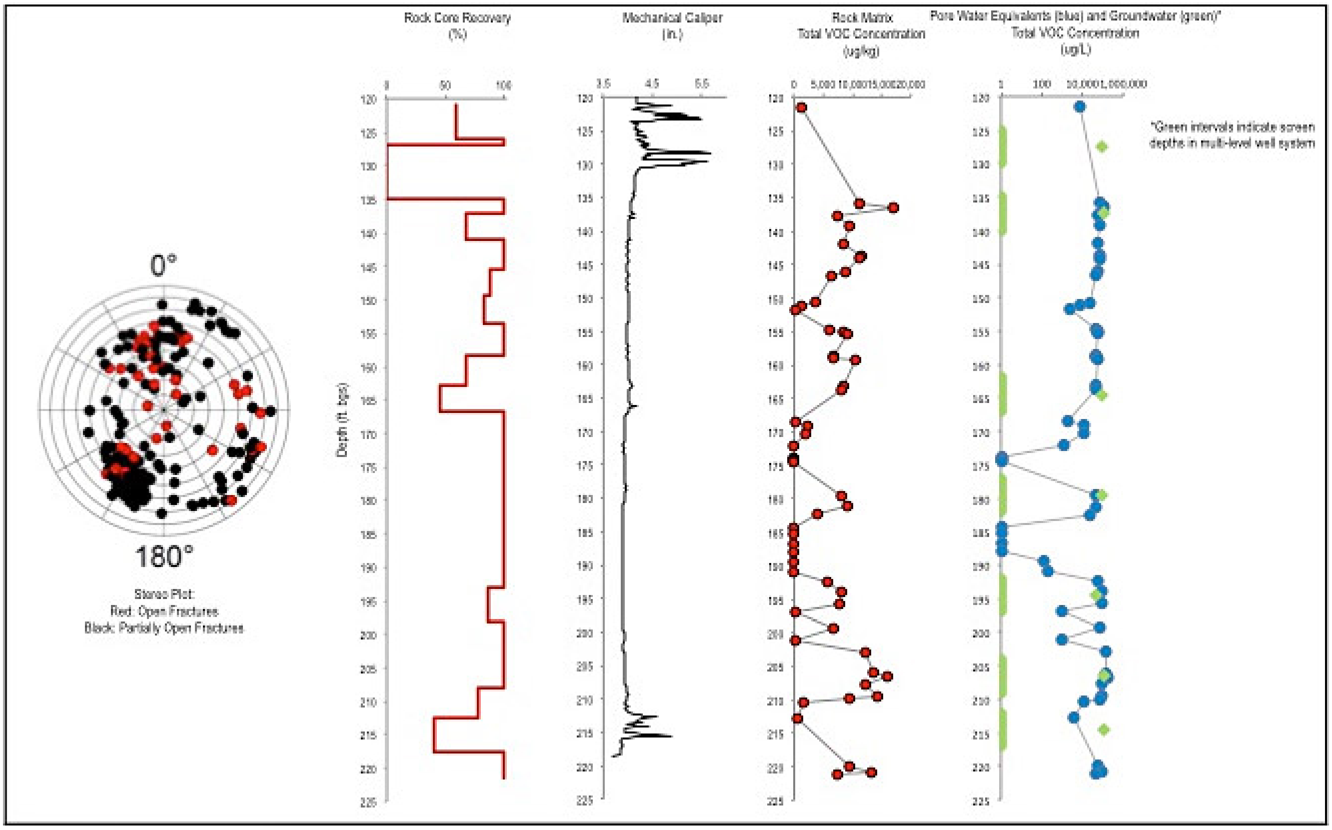


Figure 5-3. Example of a rock matrix analysis, with percent core recovery, mechanical caliper, total VOC, in a multilevel screened well system.

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.

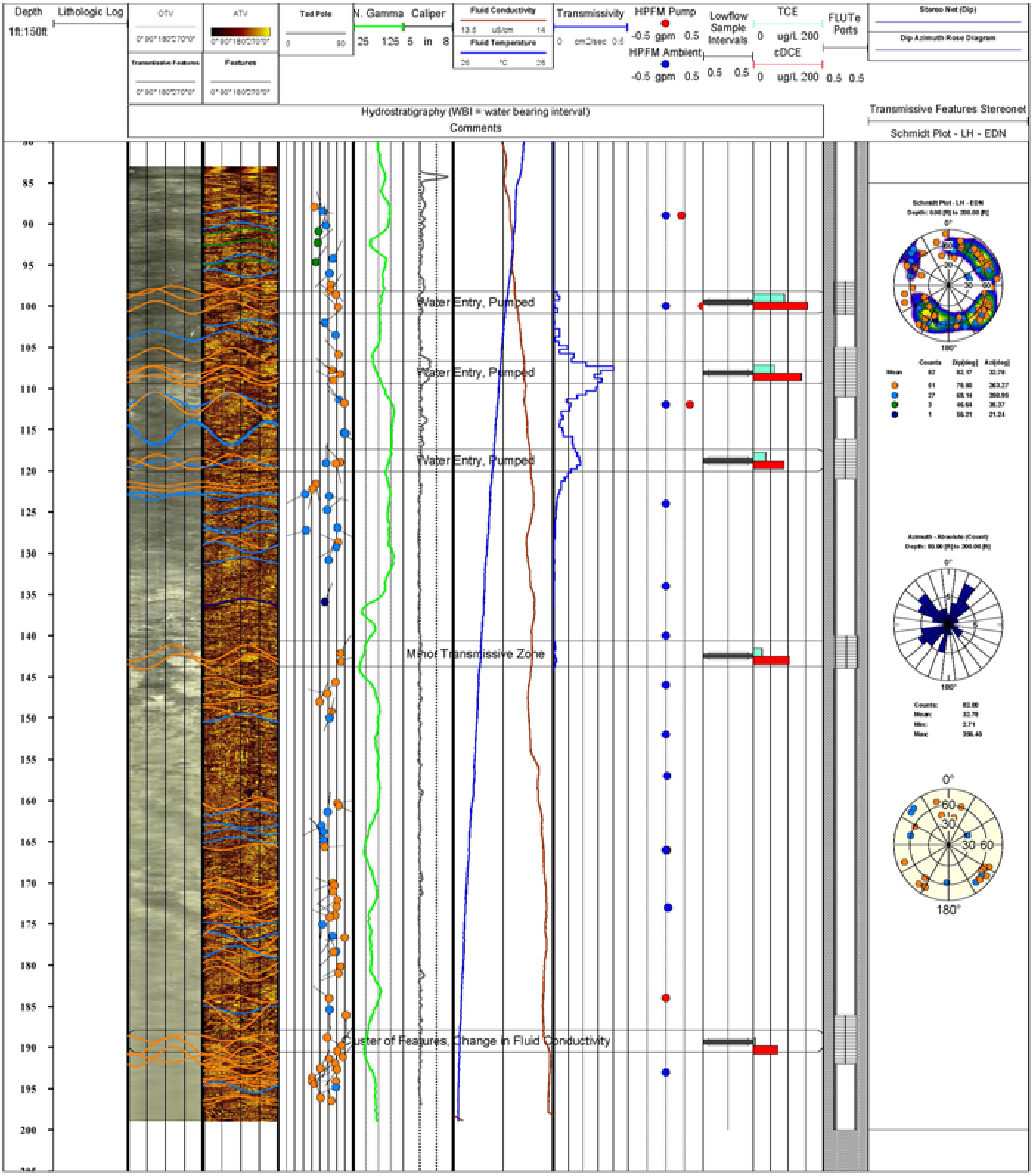


Figure 5-4. An example of an integrated borehole log.

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.

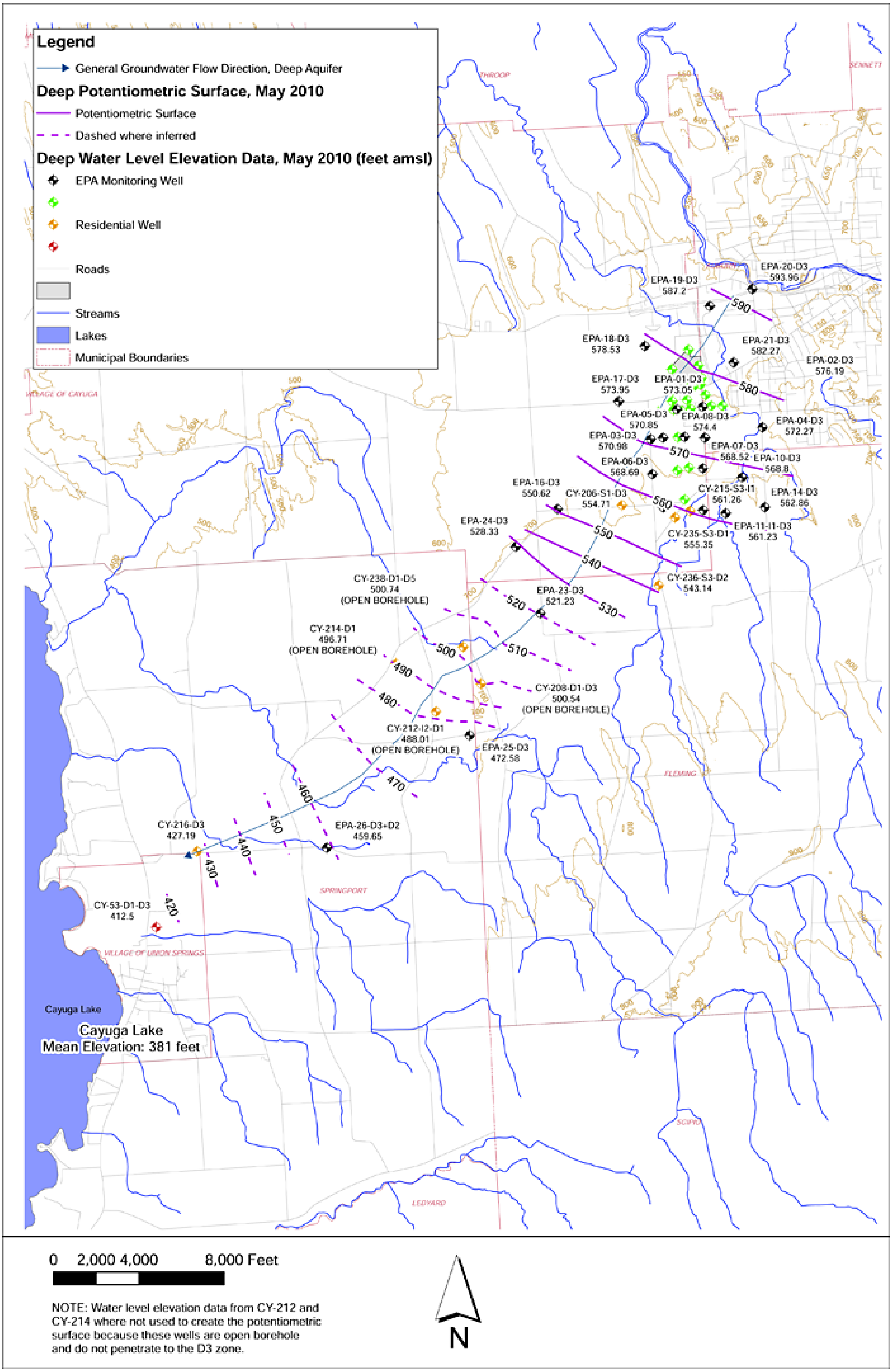
The HPFM data were added to the log and used to advance the interpretation of borehole hydraulics, fluid movement, and head distribution. Typically, the pumped and ambient logs are overlaid on one another using a common horizontal scale with zero flow in the middle, negative flow (down flow) to the left, 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	

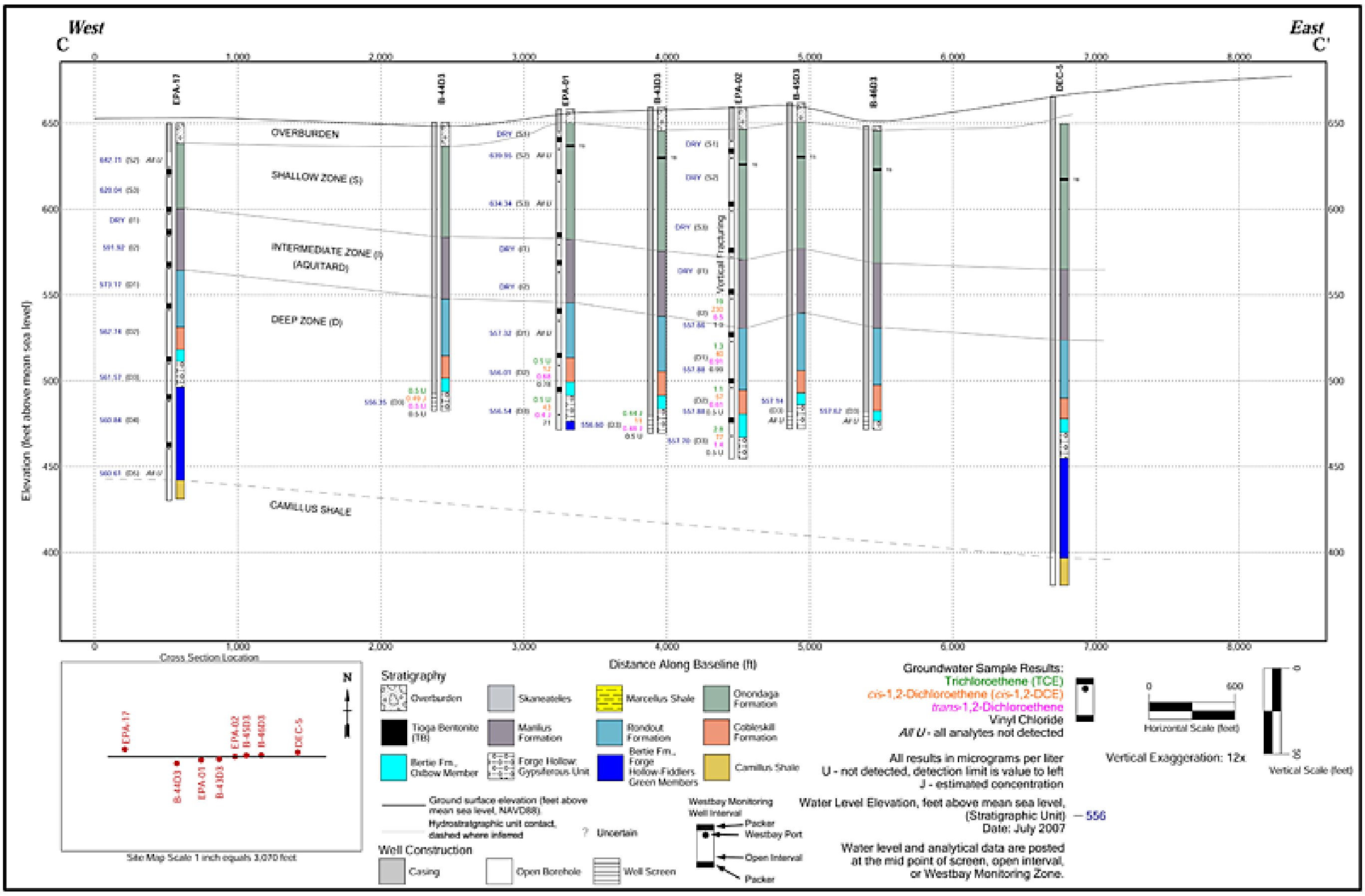


Figure 5-6. Example of a cross section used within a CSM

5.8 Lessons Learned

Characterizing and remediating contaminated fractured rock sites is difficult. Common mistakes made at these sites are summarized in Table 5-4. This table is based on field experiences of members of the authoring team regarding fractured rock sites. These common mistakes should also be considered in unconsolidated systems.

Table 5-5 Common mistakes when characterizing a fractured rock system

Common Mistake	Consequence	Remedy
Using an equivalent porous medium (EPM) CSM to investigate a fractured rock system. Scenario: The most upgradient portion of the source area has achieved contaminant reduction goals (PCE, TCE, DCE, and VC) through groundwater extraction after 10 years of operation. Other areas of the source and down gradient areas remain above cleanup criteria. Being unaware of the differences between equivalent porous medium (EPM) and discrete fracture network (DFN) conceptual models and the scale, site conditions, and data quality objectives to which they apply.	Ignores heterogeneous internal structure of bedrock aquifer system and cannot provide a reliable basis for effective delineation or remediation.	Identify a CSM that is appropriate to the site location (fractured sedimentary bedrock, igneous, metamorphic, karst) and refine through appropriate characterization. The EPM model may be sufficient if contamination is limited to shallow weathered bedrock. See Modeling.
Installing monitoring wells at equal, predetermined, or arbitrary depths from surface	Fails to recognize that transmissive fractures are not likely to be oriented parallel to ground surface. Installation of wells at equal depths often results in wells that do not intersect the same water-bearing fracture, frustrating characterization, and delineation efforts. These wells may miss the transmissive fracture zone entirely and may be open to an aquitard unit that is a poor producer of water. The upgradient portion of the source area continues to be pumped from multiple wells at a rate of 70 gpm that appears to no longer be necessary, while other contiguous areas warrant continued groundwater extraction.	The internal structure/architecture of the fracture/aquifer system must be recognized and appropriate tools used to locate transmissive fractures that control groundwater flow at the site. Surface geochemical and geophysical tools can help locate transmissive fractures and, therefore, guide monitoring well installation.

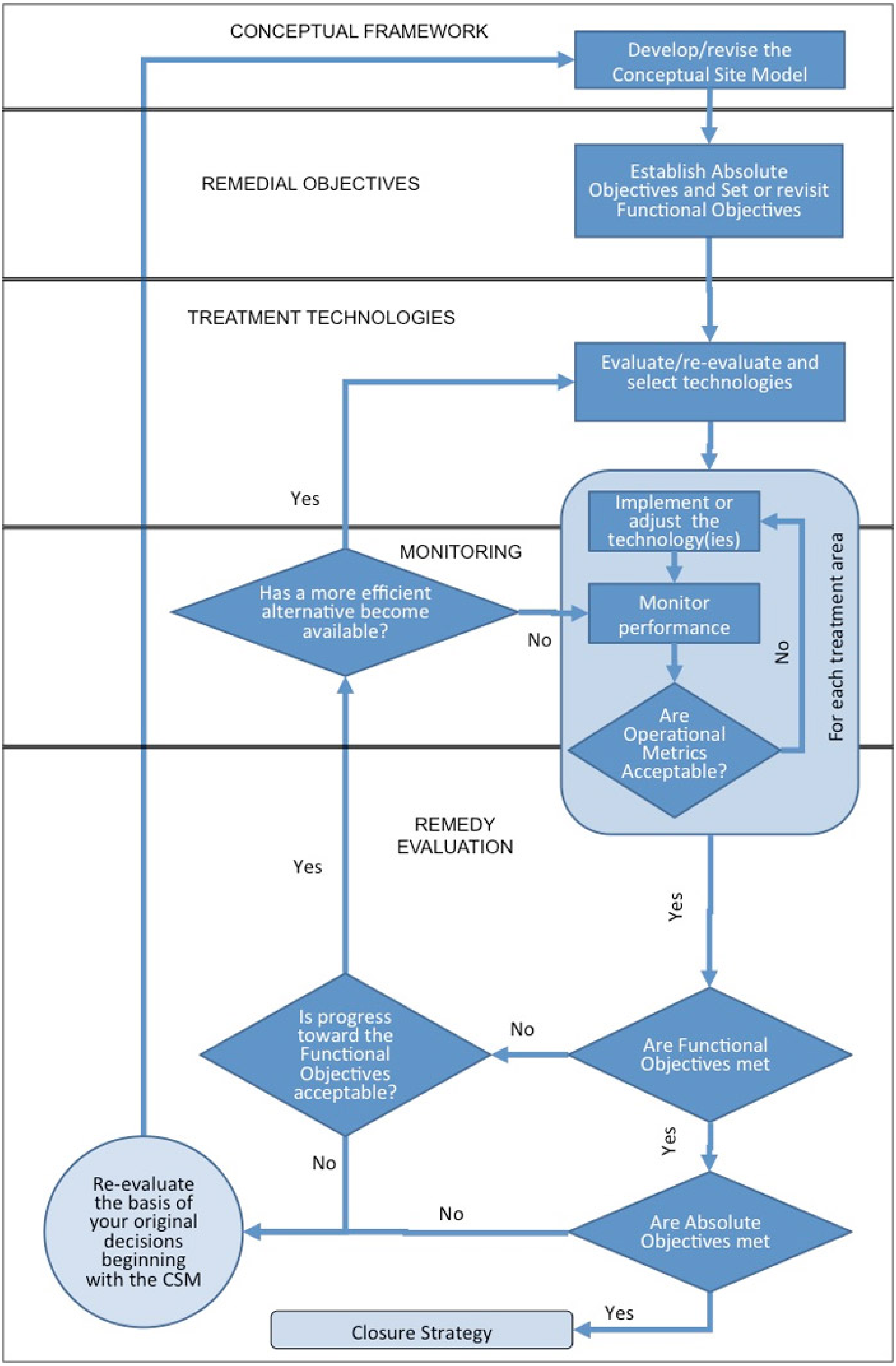
Common Mistake	Consequence	Remedy
Cross-connecting distinct fracture/water-bearing zones	Distinct fracture/water-bearing zones are sometimes cross-connected (particularly when long open boreholes are present, as in production wells) allowing contamination to vertically migrate through the borehole and contaminating deeper portions of the bedrock aquifer system.	Recognize that vertical cross-flows in an open borehole occur wherever transmissive fractures with different heads are penetrated. At DNAPL sites, an outside-in approach (USEPA 1992) should be used that requires that no borehole is drilled into the known or suspected source area until the site-specific hydrostratigraphy and source impacts on groundwater are well understood.
Preparing isoconcentration plume maps as if contamination were in unconsolidated media, without representation of fracture zones	Determine remaining uncertainty in cessation of pumping in this area to enable termination of groundwater extraction while establishing criteria for monitoring the efficacy of terminating extraction in this area. Results in inaccurate and irregular groundwater flow directions. Findings regarding groundwater flow cannot be used to support an accurate delineation of the contaminant plume.	Use only wells intersecting the same fracture/water-bearing zone to determine groundwater flow direction and assess groundwater contamination in that zone. Discrete groundwater level measurements tools such as packers to isolate each fracture to determine their head levels.
Attempted remediation prior to proper characterization of the fractured rock system. Significant data gaps.	Inadequate understanding of the internal structure/architecture of the fracture/aquifer system leads to misdiagnosis of the contamination problem which frustrates and prolongs groundwater remediation efforts. • The potential for back-diffusion from bedrock is not understood. • The contaminant data from the extraction wells may represent a composite sample and concentrations above cleanup criteria may remain in discrete fractures. • The effect of terminating pumping in this area on the overall containment system is not understood.	Proper characterization by an experienced investigator is essential to the design of an effective remediation.
Misinterpretation of vertical hydraulic gradients in a saline fractured rock setting.	Potentially developing a CSM and remedial strategy based on incorrect understanding of the vertical flow gradient.	Adjust water level measurements for salinity/density effects.
Not determining if there is vertical hydraulic flow and if it displays seasonal fluctuation.	Misunderstanding contaminant transport.	Prepare time-series plots of vertical hydraulic gradients. Use transducers to graph relationships over time to further define the system.

Common Mistake	Consequence	Remedy
Only collecting HPFM data under ambient conditions. Unclear or inadequate data collection requirements.	• Potentially misinterpreting the number of discrete samples from fractures • Fracture orientation • Fracture interconnectivity • Hydraulic conditions in a borehole, the absence of pumping	Collect data under both ambient and stressed conditions.
Disregarding historical water level data when preparing groundwater elevation contour figures.	Potentially demonstrating incorrect lateral groundwater flow directions as a result of including anomalous data.	Prepare time series plots showing historical and new water level data for each well for identifying, and evaluating/excluding, anomalous data points.
Incomplete upgradient delineation of contaminants.	May result in treatment or assumed responsibility for contamination from an upgradient/regional plume.	Perform detailed data analysis of the laboratory analytical results to confirm on-site origin.
Not investigating chemical speciation of individual plumes in a fractured rock system.	Potentially delineating the contaminant footprint as one large plume, when in fact there may be several separated plumes.	Illustrate the contaminant ratios for sampled locations and focus on the distribution of “tracer compounds”, which are low concentration constituents that would otherwise go unnoticed.
Incomplete vertical delineation of contamination as a result of only sampling fractures with the highest transmissivity.	Collecting water samples that are biased low (diluted) when there may be fractures with less flow but higher concentrations.	Use geophysical logs or other transmissivity data to select multiple sample depths. Use discrete sampling methodology to determine the most transmissive zones and properly determine contaminant concentrations in each zone. Go to the tools/techniques table for: • Discrete sampling • Orientation • Connectivity
Not recognizing that the water level in an open borehole is often not the water table, but instead is either: 1) the head of a single confined fracture, or 2) the composite head of multiple confined fractures.	Incorrect interpretation of head distribution, gradient and flow.	Use borehole logging to identify transmissive fractures and packers (or equivalent) to quantify discrete fracture heads. Conduct testing to verify if it is a concern, packing and temperature and downhole conductivity monitoring can help to define active gain and loss fractures as well as to map the most dominant flow zones.
Not understanding how/where to sample an open borehole with inflowing and outflowing fractures.	Samples will likely underestimate the maximum concentration in a fracture.	Target transmissive fractures for sampling. Conduct testing to verify concerns; packing and temperature and downhole conductivity monitoring can help to define active gain and loss fractures as well as to map the most dominant flow zones.
Not taking full advantage of outcrops for observing and measuring fractures.	Missed opportunity for Free data. The Structural component of the CSM will be less thorough. May miss vertical or near vertical fractures, which are underrepresented in vertical boreholes.	The right cell should include: Included a qualified field geologist on the team.

Common Mistake	Consequence	Remedy
Drilling deep, open boreholes through contamination; especially in areas with difficult to predict fracturing.	Cross-contaminating previously clean zones.	Assemble an experienced team of a driller/assistant and geologist who communicate and work well together. Stop at the first water-bearing fracture and sample with rapid turnaround (consider an on-site lab). Build flexibility into the plan. Be prepared to grout the hole. If the well is deep, be prepared to drill through a grouted hole. A vertical aquifer sampling program is highly recommended starting from top to bottom with a drilling program that prevents fluid movement between zones during collection of the samples. Casing advancement, grouting, packers, and a combination of techniques may need to be applied to properly characterize contaminant distribution on a newly investigated site
Not accounting for the effect of active supply wells on changing the gradients and contaminant transport.	Mischaracterization of a plume, putting sensitive receptors at risk.	Look beyond the boundaries of the site for pumping wells. Install pressure transducers as necessary to understand induced flow conditions.
Failure to use natural groundwater chemistry parameters to help understand groundwater flow direction.	Missed opportunity for relatively inexpensive data to improve CSM.	Include a person knowledgeable in groundwater geochemistry on the team.
Not effectively or correctly collecting or using geophysical data from boreholes.	Missed opportunity to collect valuable information on: fracture locations and orientations; relations of fractures to stratigraphy; zones of inflows and outflows; borehole conditions such as rugosity and breakouts; and profiles of hydraulic conductivity. If information is improperly used or misinterpreted (generally due to an untrained or inexperienced person working with the data), inconsistencies with other data sets or incorrect input to the CSM could result.	Include professionals who are knowledgeable about borehole geophysical and hydrogeophysical logging and testing in the site characterization team from the beginning.

6 Remediation Design

This chapter describes a framework for developing cleanup objectives and a remedial approach for contaminated fractured rock sites. The framework includes the essential elements necessary for effective, and adaptive, remedial decision making at these challenging sites. Figure 6-1 describes the framework for decision making (ITRC 2011), which is used to develop a CSM, set remedial performance objectives, and evaluate remedial options. The CSM is a living document that is refined throughout the process of developing and implementing a remedy, as well as during the subsequent performance monitoring. Using the CSM, absolute and functional objectives are developed to comply with applicable regulations and to establish metrics that are *specific*, *measurable*, *applicable*, *relevant,* and *time-bound* (SMART). Potential remedial technologies are described with a focus on key considerations for technology evaluation and selection in fractured rock. A screening matrix provided in this guidance (Table 6-2) helps the user select remedial technologies based on the characteristics of the fractured rock at a site. Once potential remedial technologies are identified, multiple alternatives can be developed to address contamination at fractured rock sites.



CONCEPTUAL FRAMEWORK
Develop/revise the Conceptual Site Model
REMEDIAL OBJECTIVES
Establish Absolute Objectives and Set or revisit Functional Objectives
TREATMENT TECHNOLOGIES
Evaluate/re-evaluate and select technologies
Yes
MONITORING
Implement or adjust the technology(ies)
Has a more efficient alternative become available?
Monitor performance
No
No
For each treatment area
Are Operational Metrics Acceptable?
REMEDY EVALUATION
Yes
Yes
No
Is progress toward the Functional Objectives acceptable?
Are Functional Objectives met
Yes
No
No
Re-evaluate the basis of your original decisions beginning with the CSM
Are Absolute Objectives met
Yes
Closure Strategy

Figure 6-1. Remedial strategy development flow chart (ITRC 2011)**.**

6.1 Remedial Objectives

A conventional objective of site restoration is to achieve prescribed cleanup levels such as MCLs for groundwater. Attaining low cleanup levels (such as drinking water standards) at fractured rock sites is often more challenging than at overburden sites, and may be technically or economically impracticable within reasonable time frames. Remedies can be developed, however, that address the most critical risks, foster partial cleanups, and address community concerns with more reasonable time frames and costs while continuing progress toward complete restoration in the long term. This approach is particularly applicable when distinguishing between source area and plume area remedial goals and remedies. Remedy implementation requires careful development of reasonable functional objectives for actions that may not meet the concentration-based criteria established in regulations, but that will provide benefits. These benefits include reduction in risk and contaminant mass flux, development of sites, and a transition to passive remedial options such as MNA, if appropriate.

The process for developing remedial objectives for fractured rock sites is similar to that for overburden sites. That process is described in detail in previous ITRC guidance (ITRC 2011), Chapter 3) and is only briefly summarized here. The primary difference for fractured rock is that the additional complexities and challenges of bedrock sites must be considered, particularly for development of functional objectives.

Absolute objectives are based upon broad societal values and upon state or federal regulations, such as protection of public health and the environment, protection of natural resources, and preservation of beneficial uses of groundwater. Functional objectives include steps or activities taken to achieve the absolute objectives. Functional objectives should conform to SMART attributes: specific, measurable, attainable, relevant, and time-bound (Doran 1981). A discussion of the reasoning for and development of SMART functional objectives is provided in previous ITRC guidance. Functional objectives are Remedial Action Objectives (RAOs), which are the objectives for a given set of actions, and can be interim or final. At many contaminated sites the functional objectives established for short-term actions do not represent final, or absolute, RAOs because the final RAOs often are not attainable in a reasonable time (less than 20 years or so).

Meeting all properly constructed and complete functional objectives should ensure that the absolute objectives are attainable. Examples of generic absolute and functional objectives for a contaminated fractured rock site are shown in Table 6-1. The generic absolute and functional objectives in Table 6-1 are not significantly different from those that might apply for unconsolidated media. More specific SMART functional objectives may be developed for fractured rock sites, as illustrated in the case example at the end of this chapter and with the discussion of remediation objectives as they relate to the monitoring strategy.

Table 6-1. Examples of possible generic objectives for contaminated fractured rock sites

Absolute Objectives
• Protect human health and the environment. • Conserve natural resources. • Address adverse community impacts (for example, beneficial use impacts to groundwater). • Minimize the burden of past practices on future generations.
Functional Objectives
Risks • Prevent active adverse human exposure via groundwater or vapor. • Prevent active ecological exposure via groundwater or vapor. • Prevent adverse work-related exposures via groundwater, vapor, or both. • Avoid actions that create new risks (do no harm).
Extent • Prevent expansion of source zones and extent/flux of dissolved contamination • Reduce the extent of source zone and extent/flux of dissolved contamination
Longevity • Reduce the time during which contaminants in source zones and within the dissolved extent of contamination provide persistent releases to the groundwater, vapor, or both.

Regulatory • Comply with local, state, and federal regulations.
Community • Address adverse impacts to communities.
Land Use • Restore beneficial use of impacted lands.
Economic • Select actions that have practical near-term capital costs and minimal life-cycle cost. • Avoid undue interruptions to communities, government, and industry activities. • Remove or control adverse impacts to property values.
Sustainability • Select measures that have a net positive environmental benefit. • Restore the site to a state for which passive remedies control residual impacts. • Enhance the effectiveness of complementary technologies.
Resource Conservation • Limit future degradation of resources. • Restore impacted groundwater to beneficial use. • Protect sensitive ecological receptors.

6.2 Key Challenges for Remedial Design and Implementation

Although fractured bedrock remediation can present many challenges beyond those commonly encountered in overburden, three characteristics of fractured rock that present special additional challenges relative to overburden are:

1. The wide spectrum of hydraulic transmissivities and contaminant mass storage domains that may be present, within even small portions of typical sites. Remedial technologies tend to be more commonly applied in domains characterized by higher transmissivity (secondary porosity features and larger fracture apertures), whereas in sedimentary rock, much of the contaminant mass may be present within less transmissive, primary porosity storage domains. Release or diffusion of contaminant mass from primary porosity storage domains occurs over a prolonged period (similar to back-diffusion in unconsolidated media), which affects remediation effectiveness and performance monitoring.
2. Uncertainties that exist in groundwater flow patterns in fractured rock environments. Groundwater flow in fractured rock environments is generally subject to more uncertainty than in aquifers in unconsolidated media, which translates to greater characterization effort and cost and greater remediation effort and/cost, potentially without any significant improvement in overall site understanding.
3. NAPL present in fractures has significantly less water interfacial area than in granular aquifers, and NAPL saturation (the amount of NAPL present relative to fracture volume) tends to be higher in less transmissive fractures. This condition generally reduces the effectiveness of remedial processes that rely on NAPL dissolution or on chemical and biological reaction.

6.3 Development of Remedial Strategies

Considering the characteristics and challenges of understanding fluid flow and contaminant fate and transport in fractured rock, remedial strategies that may be successful at unconsolidated media sites may not apply to fractured rock sites, or may require special additional design considerations to be effective. This section offers strategies for developing a remedial approach to fractured rock sites.

6.3.1 Focus on RAOs and Risk Reduction

Given the challenges associated with remediation in fractured rock, at some sites achieving absolute objectives or low prescriptive cleanup standards may not be realistic within a reasonable timeframe or cost, or due to technical limitations. Developing SMART functional objectives with a focus on risk reduction may be an appropriate strategy for these sites, while continuing progress toward complete restoration in the long term. Stakeholders should be engaged early in the remedial decision-making process at these sites. Important considerations include how a focus on risk reduction (rather than complete restoration) in the short-term affects community perception. Stakeholders should be informed about unremediated sources, long-term institutional controls, loss of resources, and property that will not return to beneficial use.

A receptor risk evaluation is a common component of a site investigation and is a critical component of assessing remedial options. Receptor risk evaluation is an ongoing process that continues through the life of a project. Groundwater discharge and vapor intrusion are two receptor risk components whose characteristics in fractured rock may be very different from that of overburden aquifers.

6.3.1.1.1 Groundwater Discharge

Groundwater from fractured rock aquifers may discharge to springs or other surface water bodies (wetlands, creeks, rivers, ponds, lakes), to potable wells located within or downgradient of a plume, or from abandoned mine openings. These discharges can affect receptors due to contaminant discharge and thus affect RAO development. The discharges also must be considered during remedial design. For example, the risk of discharge of a chemical reagent injected as part of a remedy must also be considered because in some cases groundwater flow in fractured rock aquifers may be fast, or discharge locations may be far from injection locations. Remedial goals and design should consider how the remedies will protect groundwater discharge areas and protect existing and future receptors.

6.3.1.1.2 Vapor Discharge

Vapor intrusion into overlying buildings may also occur from contaminated fractured rock. Vapor can be transmitted directly through vertical fractures or from fractured rock through overburden soil to the receptor. In settings with near-surface bedrock, buildings, utilities, and other structures may be constructed in direct contact with fractured rock. The potential for vapor intrusion and the rate at which it occurs can be greater in shallow bedrock, and migration endpoints may be less predictable compared to unconsolidated media (KDHE 2016). Evaluation and presence of a vapor pathway should be included in the CSM. Vapor pathways should also be considered during development of the RAOs, remedial design, and remedial action to understand how vapor risks may be affected, and to ensure that the selected remedy is protective and does not negatively affect receptors.

6.3.2 Address Contaminant Source Areas and Back-Diffusion

Source mass reduction, or mass flux reduction, may provide a realistic path forward with achievable goals, instead of attempting to treat the entire extent of contamination. A strategy focused on source treatment alone may not be sufficient where contamination has already migrated away from the source area and threatens human health or other sensitive downgradient receptors. The potential for matrix and back-diffusion should also be considered both within and downgradient of the source area. For example, sedimentary rock with significant primary porosity may also have a significant amount of contaminant mass contained in that primary porosity downgradient of the source area. As with sorbed-phase mass in the plume area at overburden sites, the contaminant may diffuse out of the primary porosity over an extended period of time, resulting in long-term plume persistence and continued risk even after source remediation is complete.

6.3.3 Acknowledge Uncertainty

Poor characterization and or invalid assumptions have historically led to failed remedies, a loss of resources, and costs to both the public and private sectors. A rigorous evaluation of uncertainty and the quality of the site characterization is therefore recommended when implementing a remedial strategy (ITRC 2012b). Consider if additional investment in site characterization may increase the probability of success for a remedy, or provide a return (in terms of lower cost) by providing more targeted or focused remedies. For example, if there is uncertainty that all source areas have been identified, then a source remedy may not be effective.

On the other hand, additional investment may not be necessary if the resulting data are unlikely to translate to a significant improvement in effectiveness or reduced cost of a remedy. For example, installation and testing of additional wells may allow a 3% to 5% reduction in uncertainty in aquifer transmissivity for a groundwater extraction system, but a small increase in pump rate may result in an effective remedy regardless of the uncertainty. Risk mitigation strategies that incorporate redundant or overly conservative assumptions and solutions due to uncertainties may increase cost and scope without providing any meaningful benefit. Thus, when making these decisions, acknowledge remaining uncertainties while developing a remedial strategy, and seek feedback while performing remediation that may further refine the CSM.

6.3.4 Develop a Contingency Plan

A contingency plan is another component of a successful strategy. While field pilot tests and careful design can reduce or eliminate the risk of poor remedial performance, developing a contingency plan in advance allows site managers to respond quickly to data that suggests a remedy is no longer performing as intended. The contingency plan should include an adaptive site management strategy that acknowledges uncertainties and outlines a plan to resolve and incorporate them as needed in additional characterization, optimization of an existing remedy, or transition to an alternative remedy.

6.4 Technologies for Remediation

This section provides general guidance for screening of remedial technologies to use in contaminated fractured rock. Screening can help in selecting an individual technology or combined technologies (spatially or temporally), or may be used to develop remedial alternatives. Remedial technologies are divided into three broad categories: physical removal technologies, containment technologies, and chemical/biological technologies. Substantial overlap can exist between among these categories and some technologies can fit in more than one category. A screening matrix that evaluates each technology considering rock types and characteristics (such as primary and secondary porosity or matrix storage) is provided in Section 6.4.1.2.

The CLU-IN website hosts a searchable database of fractured rock project profiles. This database is an additional resource for screening remedial technologies and accounts for rock types, location, and other characteristics.

6.4.1.1 Key Elements of the CSM Relevant to Technology Screening

Final selection, design, and deployment of remedial technologies considers all aspects of the CSM. At the technology screening level, key elements include the remedial strategy (Section 6.3), in addition to special considerations for bedrock lithology and contaminant characteristics.

Bedrock Lithology. Many site characteristics relevant to contaminant fate, transport, storage, and remediation are directly or indirectly related to the type of rock present and associated characteristics (see Table 2-1 and Chapter 4). Initial technology screening should therefore assess the general the bedrock lithology. Bedrock can be divided into sedimentary rocks and igneous or metamorphic rocks. Each of these can be further subdivided by their origin; for example, sedimentary rocks can be divided into clastics (such as sandstone or mudstone), or chemical (such as limestone or coal), whereas igneous rocks can be divided into intrusive or extrusive rocks, and metamorphic rocks into foliated or nonfoliated.

General lithology characteristics influence hydrologic and porosity characteristics. For example, a sedimentary rock such as sandstone may have a high primary matrix porosity whereas an igneous rock such as granite may not. Rock chemistry can also significantly affect geochemical conditions relevant for in situ chemical or biological remedies. For example, groundwater within a fractured limestone bedrock aquifer may have high alkalinity, which can impede a zero-valent iron remedy due to iron carbonate precipitation on the zero-valent iron particles. Similarly, a rock with elevated reduced iron content may be amenable to an abiotic degradation technology for chlorinated solvents.

Contaminant Characteristics. The contaminants of concern and their corresponding effects on fate and transport in the rock affect remedial technology screening. For example, contaminants that readily dissolve into groundwater may exhibit strong partitioning into the rock matrix by matrix diffusion and subsequent back-diffusion following attenuation or remediation of contamination within the secondary, or fracture, porosity. Contaminants present as NAPLs may be transported great distances at a site in which the rock exhibits a network of large, interconnected fractures. Similarly, the presence of organic carbon in the rock matrix (such as coal) may affect both sorption and transport of dissolved contaminants. Certain rock types exhibit properties that are amenable to natural attenuation through abiotic or biogeochemical transformation.

6.4.1.2 Technology Screening Matrix

Table 6-2 presents a screening matrix that identifies types of technologies that may apply at a bedrock site. Further discussion of each technology with emphasis on bedrock is provided in Section 6.4.2. Variations in bedrock physical, hydrologic, chemical properties, and time since release for NAPL at a site must be considered carefully during remedial technology selection. For example, at a granitic bedrock site with little primary porosity or matrix storage, but high secondary porosity, technologies such as pump and treat or an ISCO approach with a short-lived oxidant may be appropriate. In contrast, if a site has shale or sandstone bedrock with both appreciable primary porosity and matrix storage, then technologies or strategies with long-lived reagents or a thermal approach could be considered. This matrix is not intended to provide a site-specific solution, but rather to assist with an initial screening of technologies or combinations of technologies. Characteristics and remedial objectives must ultimately be evaluated on a site-specific basis.

Table 6-2 summarizes hydrology characteristics relevant to remedial screening and ranks their applicability as "high" (H) or "low" (L). The lower portion of Table 6-2 lists the applicability of technologies, and the presence or absence of contaminant mass as NAPL, in matrix storage, and matrix and fracture transmissivity.

The applicability of technologies to certain rock types and settings in Table 6-2 was assigned values of "Y" (yes), "N" (no), or "U" (unlikely). These values are intended as general guidance based on the professional judgment and experience of the ITRC team. A value of "N" or "U" should not be interpreted as a conclusion that a technology cannot or should not be applied at a site with the associated characteristics. Ultimately, that decision must be based upon site-specific characteristics, remedial strategies, and objectives. In addition, innovations in design can advance technologies for successful applications at sites that do not currently seem to be good candidates for those technologies.

Table 6-2. Remediation technology screening matrix for fractured bedrock environments.

Click Here to view Table 6-2 in Adobe Acrobat format.

6.4.2 Remediation Technologies for Bedrock

General types of technologies are discussed in this section, with an emphasis on special characteristics or considerations for design and implementation in bedrock. The CLU-in website includes bedrock remediation case studies, organized by remedial technologies. The CLU-in site also includes a database of fractured bedrock project profiles that is searchable by both remedial technologies and keywords.

6.4.2.1 Physical Removal Technologies

Physical removal technologies are those that recover contaminants from bedrock. These technologies range from direct physical removal methods such as excavation, to indirect removal methods such as multiphase extraction and thermal treatment (which rely on physical properties of the contaminant, such as volatility, for removal). Physical removal technologies are more commonly applied to source areas due to technical feasibility and cost considerations.

Removal ▼*Read more*

Removal (excavation) of contaminated bedrock is possible in certain situations. This approach could be effective with bedrock characterized by high primary porosity and matrix contaminant mass storage, because contaminant mobility during removal will be low and because contaminant mass storage can be difficult to address with other technologies. To be successful, the contaminated bedrock zone must be accessible and the nature of the bedrock such that it can be physically excavated without enhancing contaminant migration or displacement. Physical limitations of excavation generally limit removal to relatively "soft" bedrock types, characterized by low seismic velocities (for example, sedimentary rocks such as sandstone and limestone) or weathered rock, in unsaturated environments, which can be ripped by excavating tools.

Thermal Remediation Methods ▼*Read more*

All thermal remediation methods rely on heating the subsurface to enhance removal or destruction of contaminants (primarily volatile contaminants) from the solid matrix and aqueous phases. Increased volatility or mobility of contaminants, resulting in enhanced contaminant recovery, is the most common style of application and thus thermal methods are categorized as a removal technology. Elevated temperatures, however, can also result in enhanced biodegradation and hydrolysis. Thermal remediation methods offer an advantage over chemical and biological approaches, in that direct contact and reaction of a reagent or microbial activity with a NAPL or dissolved solute is not necessary. Thermal remediation methods are accepted options for unconsolidated formations, and within the past few years have become more widely applied to bedrock.

Thermal remediation methods include electrical resistance heating (ERH), thermal conduction heating (TCH), and steam-enhanced extraction (SEE). Each type of thermal remediation method has certain individual advantages and disadvantages, depending on the different porosity and matrix storage characteristics of bedrock. SEE methods flood the bedrock formation with fluid. These methods apply to sites with high secondary porosity and large fracture apertures, but may be less effective for sites with high matrix storage or fracture zones with lower transmissivity. ERH methods pass an electrical current primarily through water in the system entrapped around rock grains. When the primary porosity is negligible, the electrical current flows through the fractures and the rock is heated only by thermal conduction. ERH is, therefore, generally more applicable to sedimentary rock types (except for coal-rich formations) with relatively high primary porosity. ERH methods cannot achieve temperatures greater than the boiling point of water. TCH methods rely upon heat conduction through the rock matrix, and thus can achieve higher temperatures and apply to rocks with low primary or secondary porosity. TCH is more limited by higher rates of groundwater flux than by variation in bulk rock properties (Baston 2009; Lebrón 2012).

Air Sparging ▼*Read more*

Air sparging (or air sparging coupled with vapor extraction) is widely applied to remediate volatile contaminants in unconsolidated aquifers. Air sparging (in contrast to vapor extraction) is generally not widely applied in contaminated fractured rock. Air bubbles may exhibit a greater tendency to coalesce in fractures and bypass large portions of the treatment zone, particularly at sites characterized by vertically oriented fractures. Variable and elevated pressures may also reduce compressor lifetime.

Vapor and Multiphase Extraction ▼*Read more*

Vapor extraction methods are widely applied to volatile contaminants in unsaturated zones, including in bedrock. Vapor extraction is a typical component of thermal remediation methods, and can been combined in bedrock environments with other technologies such as with in situ chemical oxidation (Cho 2002). The vapor migration pathway characterization, and hence vapor extraction system design, may be more challenging relative to overburden due to discrete fracture control of vapor migration in bedrock. The characterization must define fracture geometry and potential vapor flow pathways for effective remedial design.

Multiphase extraction is also widely applied to volatile contaminants in fractured rock sites. Multiphase extraction typically combines vapor extraction with groundwater and LNAPL extraction. Like vapor extraction alone, vapor and fluid migration pathway characterization, and hence multiphase extraction system design, may be more challenging than overburden due to discrete fracture control of vapor migration in bedrock.

Surfactant/Cosolvent Flushing ▼*Read more*

With surfactant/cosolvent flushing, a compound that enhances mobilization or solubilization dissolution of a NAPL is injected into the aquifer, and the injected compound (along with the solubilized dissolved or mobilized NAPL) is subsequently extracted. An advantage of this technology in bedrock is enhanced recovery of relatively insoluble NAPL phases that may be immobilized on fracture surfaces, such as coal tar. Specific challenges to using this technology in fractured rock are related to fluid movement and collection. The injected fluid preferentially migrates through highly transmissive, large-aperture fractures associated with secondary porosity, with little or no contact with NAPL in less-transmissive fracture zones, primary porosity, or matrix storage. In addition, effective distribution and recovery of the surfactant/cosolvent is more challenging in a fractured rock environment due to heterogeneous and anisotropic fluid flow. As a result, applying surfactants/cosolvents in fractured rock aquifers is generally not recommended (ITRC 2003).

LNAPL Recovery ▼*Read more*

Techniques for LNAPL-only recovery can also be successfully applied in fractured rock settings. The methods are similar to porous media applications and include active and passive skimming, hand-bailing, passive absorption (socks), and multiphase extraction (when targeted to remove LNAPL only). The primary differences between LNAPL recovery in fractured rock compared to porous media are related to how groundwater and LNAPL migrate in the subsurface. LNAPL may be present and recoverable in multiple fractures, which may require targeting discrete fracture features with specifically-screened vertical, horizontal, or angled wells.

6.4.2.2 Containment Technologies

Containment technologies prevent or reduce contaminant mass flux and migration. Containment technologies offer little or no direct treatment of concentrated source areas, but instead protect downgradient receptors. Groundwater pump and treat systems are historically the most commonly deployed bedrock containment technology. Permeable reactive treatment zones are another containment technology used in fractured bedrock.

Groundwater Pump and Treat ▼*Read more*

Pump and treat system design and implementation in bedrock are more complex than in overburden aquifers, because bedrock aquifers exhibit greater heterogeneity and anisotropy than overburden aquifers. Considerations relevant to fractured bedrock or which are more challenging in fractured bedrock than in overburden systems include the following:

- Bedrock typically exhibits both primary and secondary porosity domains with different fluid movement and contaminant migration characteristics. Groundwater yield is derived primarily from very transmissive zones, which typically exhibit the greater mass flux but overall lower contaminant concentrations and mass. Dead-end fractures zones prevent trapped water and NAPL from being extracted. Thus, pump and treat may provide an effective containment strategy, but on the other hand provides relatively little (or very slow) mass removal.
- Relict sedimentary bedding planes may exist, with variability in primary porosity patterns resulting from grain size and distribution of the original sediment.
- Local and regional structural and tectonic effects, and evolving tectonic stress regimes, can result in fracture-dominated flow that is affected by the strike and dip of the fractures. Complex geologic histories can result in multiple intersecting fracture sets with different structural orientations. This geology complicates identification of optimal well locations and depths.
- Bedrock fracture zones may communicate with overburden or heavily weathered bedrock zones, resulting in migration of groundwater and contaminants between overburden and bedrock fractures.
- Multiple discrete or interconnected fracture zones within individual boreholes or wells, with variable transmissivity and contaminant mass flux, may require multiple, separate pumping zones within individual wells or well fields.
- Contaminants can diffuse into the secondary porosity and matrix storage domains, and then slowly back-diffuse into groundwater within transmissive fracture zones as chemical gradients change with time and plume maturity.

These factors result in unpredictable well yields, which may vary by orders of magnitude due to spatial variability in fracture characteristics. Consequently, groundwater flow or fate and transport modeling is often not a useful tool for pump and treat system design.

The hydrologic complexity of fractured rock aquifers often requires extensive study, pilot testing, and optimization to design and operate an effective system. The location and construction of the extraction network and the location of the pump within extraction wells are critical in fractured bedrock applications. Aquifer testing is needed to understand the behavior of fluid flow in the fractured bedrock. Geophysical tools can provide insight on the location and relationship of fracture features. Unlike many groundwater extraction well networks in overburden with overlapping zones-of-influence, extraction well networks in fractured bedrock instead focus on fracture flow and communication. Accordingly, an extraction well network in a fractured bedrock setting may differ during the conceptual design stage. With proper design, testing, and monitoring, pump and treat systems can be applied effectively in nearly any water-bearing rock formation, with the understanding that the system is likely to be in long-term operation unless combined with other technologies, or at sites with relatively low contaminant mass stored in primary porosity.

Permeable Reactive Barrier Zones ▼*Read more*

Permeable reactive barrier zones (PRBZs) can be constructed in fractured bedrock aquifers. For this method, a reactive material is injected into existing or induced fractures. Injected material can include ZVI, solid potassium permanganate, or a combined sorptive and reactive material such as a carbon-based substrate combined with ZVI for example. Subsequent groundwater flow through the fractures and contact with the reactive material results in treatment of the contaminants. PRBZs typically use a chemically- or biologically-active treatment medium and thus may also be considered a chemical/biological technology. However, PRBZs are included here as a containment category strategy because the primary intent of the application is to treat groundwater as it passes through the PRBZ, limiting (and containing) contaminant migration.

Numerous case studies describe chemical (oxidation and reduction), biological, or combined chemical/biological media in fractured bedrock. The Former Industrial Site, Greenville, South Carolina used hydraulic injection of a solid potassium permanganate slurry in the source area coupled with hydraulic injection of ZVI in the plume area, in both overburden and bedrock. Insoluble or low-solubility substrates such ZVI or solid potassium permanganate can provide ongoing treatment for years or potentially decades with a single injection. This single injection can address contaminants that migrate or diffuse from less-transmissive primary porosity or matrix storage domains over time. Some substrates, such as permanganate (Goldstein 2004), may also chemically diffuse into the secondary porosity domain within the bedrock matrix in addition to filling fracture zones. Considerations for PRBZs specific to fractured bedrock aquifers include the following:

- Remedial design requires accurate identification of transmissive, water-bearing fracture zones. A PRBZ remedy may be ineffective if a single transmissive fracture zone is missed. The same considerations and uncertainties regarding design of pump and treat systems also apply to PRBZs.
- Identification of the fracture interval depths is critical. Media are typically injected into existing fractures. Identifying the exact depth at which to inject with sufficient vertical resolution to target a specific fracture requires careful geologic coring and logging.
- Injected media (whether chemical or biological), or their resulting precipitates or biofilms, may affect fluid flow through the fractures. Groundwater flow may be diverted away from the media-filled fractures rather than through the treatment medium, resulting in reduced remedy performance and altered plume geometry or hydrologic properties.

In general, PRBZ technologies are likely to be most applicable to sites characterized by significant secondary porosity, which provides a location to inject the reagents effectively. Reagents are not readily injected into primary bedrock porosity. However, PRBZ reagents are typically intended to persist over many years in the subsurface, and therefore (in the presence of secondary porosity for reagent injection) can be appropriate technologies for sites with significant contaminant mass in primary porosity and matrix storage domains.

6.4.2.3 Chemical and Biological Technologies

Chemical and biological technologies remediate contamination by transformative and destructive processes such as in situ chemical oxidation (ISCO), in situ chemical reduction (ISCR), in situ bioremediation (ISB), and various combinations of these technologies. As when using these technologies in porous media aquifers, the contaminant properties, geochemistry, rock matrix properties, and presence of organics and inorganics in the matrix are important factors in remedy selection and design. Formation hydraulics, mineralogy, primary and secondary porosity, matrix storage, and fracture aperture size are considerations specific to fractured bedrock remediation for in situ technologies. For NAPL treatment, an additional challenge is that the NAPL-water interfacial area (which is exposed to reaction with chemical reagents and to microbial processes) is substantially lower than in granular porous media aquifers, and a greater proportion of the NAPL may be trapped in less transmissive fractures (Schaefer 2016). This condition can significantly reduce overall treatment effectiveness.

Selecting specific amendments at a site requires expertise and is beyond the scope of this guidance; however, general observations that are relevant at the technology screening level are presented.

In Situ Chemical Oxidation and In Situ Chemical Reduction ▼*Read more*

ISCO and ISCR are common remediation technologies applied to chlorinated compounds, petroleum hydrocarbons, and other contaminants including metals (such as hexavalent chromium, arsenate, and uranium) and anions (such as perchlorate), in dissolved, sorbed, and nonaqueous phase forms. ISCO and ISCR are versatile remedial strategies with a wide array of chemistries available depending upon the target contaminants and design objectives (ITRC 2005; Siegrist 2011).

Significant considerations for bedrock applications include reagent lifetime and distribution of the reagent through less-transmissive, primary porosity and matrix storage domains. Both ISCO and ISCR can be applied as PRBZ containment remedies. Each approach can also be applied as a source-area remedy, targeting NAPL within transmissive fracture zones using a more aggressive (but shorter-lived) reagent, such as catalyzed hydrogen peroxide (for ISCO) or nanoscale ZVI (for ISCR).

ISCO and ISCR in PRBZ design is summarized in Section 6.4.2.2, and some of the design considerations (such as potential alteration of the groundwater flow regime) also apply to source area applications. Additional considerations for source-area remedies specific to bedrock include the following:

- Reagent injection into fractured bedrock is different from injection into homogenous overburden settings. Design considerations include fracture transmissivity, orientation, and connectivity between fractures and resulting reagent distribution, particularly for shorter-lived reagents such as catalyzed hydrogen peroxide (for ISCO) or liquid reductants such as calcium polysulfide (for ISCR). Highly transmissive fractures carry injected reagents but may not deliver them to the target treatment area. Dispersion may be successful in transmissive zones but resulting contact time may be limited by the rate of groundwater flow. The density of some liquid reagents is significantly different from water, and thus density-driven flow (for example, of a relatively dense oxidant solution down-dip) may result in unexpected reagent distribution.

- Oxidant or reductant demand from fractured rock is generally much lower than for overburden aquifers. In overburden, the reagent is intended to permeate the formation. Mineral surfaces exert a primary demand for oxidants and reductants, and the amount of surface area that reagents contact in overburden is large (reflecting better reagent distribution). In contrast, in bedrock the reagents primarily contact fracture faces, rather than permeate intergranular primary porosity, and the corresponding rock surface area exposed to react with the oxidants or reductants is much lower. As a result, particularly with reagents injected as liquids, oxidant or reductant demand must be carefully considered to mitigate risks associated with adding too much reagent.
- Back-diffusion of dissolved contaminants from less-transmissive portions of primary porosity or from matrix storage domains remains a significant area of concern in bedrock. Back-diffusion can result in apparent rebound following ISCO or ISCR applications in which the oxidant lifetime may be relatively short. While the potential for back-diffusion of contaminants from bedrock is known, the duration and magnitude may not be well understood. Certain long-lived reagents, such as permanganate, may diffusively penetrate the bedrock (Goldstein 2004) and thereby address organic contaminant back-diffusion.
- ISCO is often used as a source remedy to address NAPL. In fractured rock, the interfacial surface area of NAPL droplets or pools exposed to reaction with the oxidant is much lower than in granular aquifers, and NAPL may be trapped in less-transmissive fractures with little or no exposure to oxidant. The lack of exposure to the oxidant reduces treatment efficiency and potential effectiveness, particularly for short-lived oxidant systems (Schaefer 2012).
- The effectiveness of most ISCO and ISCR reagents is sensitive to groundwater and rock chemistry. However, in a fractured rock environment, the amount of rock surface area exposed to reagents within fractures is much lower than the granular surface area of each grain in an overburden aquifer. As a result, commonly-recognized limitations to these reagent systems resulting from rock lithology or chemistry in overburden aquifers are often less important in fractured rock. For example, a mildly acidic pH range optimal for catalyzed hydrogen peroxide may be difficult to achieve in a carbonate-rich overburden aquifer, but that same pH shift will be easier to achieve in fractured rock because there is significantly less carbonate mineral surface exposed to reaction on a fracture face. Stop read more

In Situ Bioremediation ▼*Read more*

In situ bioremediation (ISB) is a commonly used technology that offers a wide array of chemistries and modes of injection. For example, solid and liquid reagents, a range of viscosities and densities of liquid reagents, reactivity, lifetime and direct source application, and PRBZs in fractured rock applications can address organic compounds, metals, anions, and other contaminants. ISB in fractured rock also shares many of the specific challenges as those for ISCO and ISCR reagents, including preferential delivery of reagents to relatively transmissive fracture zones, inability to address contaminant mass trapped in primary porosity or in matrix storage domains, reduced NAPL-water interfacial area, and density-driven flow.

Special challenges unique to ISB in fractured rock include the distribution of microbial fauna between groundwater within fractures and the primary porosity of the fractured rock matrix, and the potential effect of biofilm growth on groundwater flow in transmissive intervals. Characterization of microbial activity and ISB processes in fractured rock aquifers has primarily focused upon the planktonic or suspended biomass in groundwater, or groundwater geochemistry within transmissive fracture zones (Hohnstock-Ashe 2001). A more abundant microbial mass and activity, with a different species diversity and physiology, may be associated with biofilms attached to fracture surfaces and even within the rock matrix (Lima 2012) Whether microbes can migrate into and survive within the primary porosity of the rock matrix is not known. In one study of a sandstone rock matrix, (Lima 2012) found a variety of dechlorinating bacteria as much as 64 cm away from the nearest discrete fracture. Stimulated biofilm growth on fracture surfaces resulting from injection of a carbon amendment may also reduce fracture transmissivity, affecting groundwater flow patterns within transmissive fracture zones. For example, one study reported two to four orders of magnitude decrease in transmissivity within 20 to 60 days of the onset of biostimulation (Smith 2010).

Given the presence of microbial activity potentially deep within the primary porosity domain, ISB can likely be applied to a wide variety of rock environments. The potential lifetime of ISB substrates is another design factor. Short-lived substrates may be most applicable where there is low primary porosity or matrix storage, while longer-lived substrates may provide an effective solution even for sites with significant primary porosity and matrix storage contaminant mass.

Monitored Natural Attenuation ▼*Read more*

Some contaminants may be amenable to natural attenuation mechanisms. This approach not only includes typical attenuation mechanisms such as advection and diffusion, but also abiotic reduction or biogeochemical transformation of certain contaminants such as chlorinated solvents. High iron or sulfate content in certain rock matrices may trigger abiotic reduction mechanisms or stimulate biogeochemical transformation. While these attenuation mechanisms are not unique to fractured rock, understanding how rock mineralogy benefits these mechanisms can inform the characterization and remedial development stages. Additional information regarding abiotic degradation and biogeochemical transformation are documented in ITRC guidance (ITRC 2011).

6.4.2.4 Innovative and Combined Remedies

Contaminated fractured bedrock sites often present a unique set of site conditions that require development or modification of typical remedial approaches. Innovative technologies, such as electrokinetic remediation, may offer special advantages in fractured rock settings. Coupling multiple technologies customizes remedies to address the wide range of conditions present at typical hazardous waste sites. Technologies can be coupled in time (one technology followed by another technology in the same treatment area), space (different technologies applied simultaneously in different parts of the site), or both.

Certain combinations of technologies, for example ISCO with ISB, or ISCO with ISCR, were historically considered incompatible with each other. Recently, however, integration of multiple technologies (including technologies historically considered incompatible) has been found to provide yield synergistic benefits for effective site remediation (ITRC 2011). For example, ISCO and ISCR have been applied successfully in different portions of a fractured bedrock site impacted with DNAPL (see the Former Industrial Site case study). As another example, the biogeochemical reductive dechlorination (BiRD) process can be combined with ISB to stimulate microbial reduction of native iron and formation of reactive iron sulfide minerals. These reactive minerals are capable of abiotic reaction and destruction of contaminants such as certain chlorinated VOCs. As with coupled technology applications in overburden (ITRC 2011), combined technology remedial designs for bedrock must account for the potential interactions of the different technologies in time and space.

6.4.2.5 Bench and Field Pilot Test Considerations

Bench and field pilot tests can provide important, site-specific information for remedy evaluation and design. Contaminant treatability, rock-chemistry interactions, reagent distribution, long-term treatment prospects, and overall effectiveness at a field-scale for a technology in a fractured rock aquifer may be different than in overburden. Several case studies offer examples of how bench and field pilot tests have been performed for a variety of site conditions. Bench and field pilot tests for fractured rock sites have two key considerations that differ from granular overburden sites: rock surface area and reagent transport.

Rock Surface Area

The rock surface area exposed to groundwater, contaminants, and reagents is different in fractured rock relative to overburden, and is important for all stages, from bench test to full-scale implementation. Bench testing for remediation technologies that are strongly influenced by interaction with particle surfaces (such as chemical and biological technologies) must account for this difference. For example, bench tests of oxidant demand or pH buffering of a relatively short-lived reagent in a fractured granite rock with little or no primary porosity should analyze the reagent solutions only in contact with natural fracture surfaces. One method to restrict reactions to only fracture surfaces is to coat the “cut” surfaces of rock cores with epoxy or other nonreactive material and immerse the fracture face in the solution under evaluation. These tests should not be conducted with crushed rock samples, or with core segments in which portions of the drilled surface of the core (as opposed to just the natural fracture surfaces) are exposed to the reagents. Using crushed rock or drill core surfaces exposes fresh, unweathered mineral surfaces to the reagents, which would not normally occur in field conditions.

Reagent Transport

Fracture-controlled groundwater flow in bedrock can be much faster than typically observed in overburden aquifers. This factor must be considered when evaluating remedial technologies, and especially when evaluating technologies that rely on fluid flow, such as injection of a soluble chemical or biological reagent. The much smaller rock surface area exposed to reagent interaction in bedrock aquifers relative to granular overburden aquifers strongly affects characteristics such as oxidant demand and pH shifts. This reduced surface area is significant for technologies such as in situ chemical and biological methods, which require injection of a reactive reagent. The differences in reactivity associated with surface area also affect reagent transport. The reduced surface area exposed to reaction may translate to less degradation or reaction of a reagent, which therefore results in increased reagent transport. This result must be considered for the following reasons:

- Injected reagents may be transported far greater distances and in far shorter time frames in fractured bedrock aquifers than in granular overburden aquifers. At sites where groundwater discharges to surface water (by springs, for example) or other receptors, the risk of reagent discharge must be evaluated.
- Transport of liquid reagents preferentially follows transmissive fracture networks. At many sites, the contaminant mass and flux are lowest and reagent transport is greatest in the most transmissive zones. Thus, a liquid reagent injection may initially exhibit a large radius of influence and effective reductions in groundwater contaminant concentration or flux. But at sites with high primary porosity, the contaminant reductions may be short-lived due to mass flux from less transmissive zones, primary porosity, or matrix storage domains.
- Transport of nonaqueous liquid reagents (such as vegetable oils) or of aqueous solutions with high concentrations of dissolved solutes (all of which affect viscosity and density) may also be different in fractured rock. These fluids exhibit a greater tendency to float or to sink within fracture networks due to the contrast in density and the greater size of fracture aperture relative to intergranular pore throat diameter.
- Dilution characteristics of injected reagents in fractured bedrock may be different from typical overburden sites. For example, reagents may be diluted due to distribution over larger radii of influence, or could be concentrated at greater distances due to flow in relatively small but very transmissive fractures.

6.5 Case Example

The Former Industrial Site in Greenville, South Carolina, provides a case study for the remedy selection process. Further details regarding the site conditions, remedial actions, and results are provided in the full case study. In summary, an estimated 1,365 gallons of trichloroethene (TCE) were released to the environment at the site between approximately 1991 and 1996. The source area lies near the top of a hill and the groundwater plume in the saprolite and bedrock occupies approximately 15 acres. Groundwater is naturally relatively acidic (pH approximately 5.2), thus there is little biodegradation occurring. The resulting groundwater plume in saprolite overburden and bedrock is approximately 15 acres. The bedrock is a foliated schist and gneiss metamorphic rock, with discrete relatively horizontal, transmissive fracture sets, and low primary porosity or matrix storage.

6.5.1 Objectives

This example site illustrates how difficult, yet important, it is to define the absolute objectives and associated SMART functional objectives for remediation of the site.

6.5.1.1 Site Risks

A potential risk to human health at this site is vapor intrusion into the building adjacent to the source area (Figure 6-2). Piping and appurtenances related to TCE use at the facility were removed. Unsaturated soil in the source area was previously remediated by a combination of soil removal, soil vapor extraction, and in situ thermal desorption. Results of subsequent vapor sampling inside the building yielded initial cancer screening risks well below the 1.0×10^{-6} threshold, thus there is no unacceptable risk to workers. TCE and cis-1, 2-dichloroethene migrated off site in groundwater, but no residences or other actively occupied buildings overly the plume and groundwater is not used. Groundwater flows towards a local river adjacent to the site.

The responsible party no longer owns the property but retains liability for the remediation. The building is currently used as a warehouse and for light industrial purposes. The primary driver for site remediation is the off-site migration of impacted groundwater and potential discharge to the local river. The goal of the responsible party is to remediate the site groundwater to MCLs within 15 years to eliminate their ongoing liability in a reasonable timeframe.

6.5.1.2 Absolute and SMART Functional Objectives

The absolute objectives for the site were established as the following:

1. Protect human health and the environment.
2. Mitigate off-site migration of contaminants and potential impact to surface and groundwater resources.

The site investigation demonstrates the following:

1. High concentration and likely DNAPL in the aquifer in the source zone provide an ongoing TCE source to groundwater.
2. TCE and degradation products in the plume zone (groundwater and sorbed) result in off-site migration and

potential discharge to a surface water body.

Although high TCE concentrations are in the source area groundwater, the aquifer is approximately 55 feet below grade in the source area and the saprolitic soil has low permeability, which helps mitigate vapor risks. Vapor sampling inside the building confirmed the absence of vapor risks to workers.

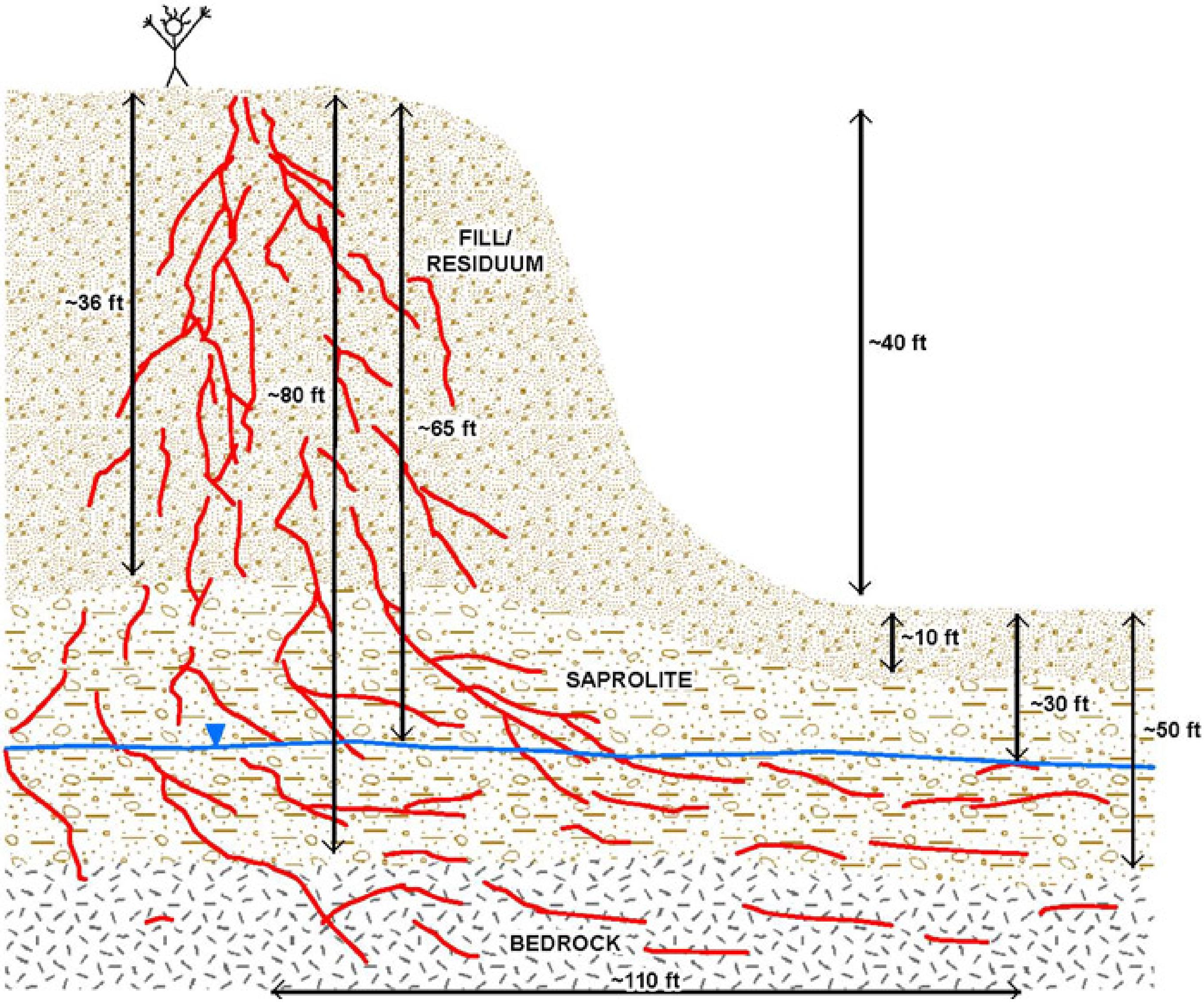


Figure 6-2. Cross-sectional schematic illustrating potential pathways and risks at the Former Industrial Site, consistent with the 21-Compartment Model in Table 6-4.

Table 6-3. Absolute and functional objectives and SMART attributes for Former Industrial Site.

Absolute objective #1: Protect human health and the environment.

Absolute objective #2: Mitigate offsite migration of contaminants and potential impact to surface and groundwater resources

Functional objective #1: High concentration and likely DNAPL in the aquifer in the source zone, providing an ongoing TCE source to groundwater: Eliminate DNAPL and reduce groundwater VOC concentrations to MCLs within 15 years, to eliminate ongoing source of VOCS to plume area

- Specific - Yes: defines a numeric treatment objective and treatment area.
- Measurable - Yes: achieve MCLs in groundwater samples.
- Attainable - Yes: an aggressive source-area ISCO remedy has been implemented.
- Relevant - Yes: source elimination will mitigate further offsite plume migration.
- Time-bound - Yes: 15 years.

Functional objective #2: TCE and degradation products in the plume zone (groundwater and sorbed), resulting in offsite migration and potential discharge to a surface water body: Reduce dissolved and sorbed-phase contaminant mass to MCLs within 15 years, to eliminate further offsite migration and potential surface water discharge

- Specific - Yes: defines a numeric treatment objective and treatment area.
- Measurable - Yes: achieve MCLs in groundwater.
- Attainable - Yes: a series of ZVI permeable barriers were constructed which, based upon modeling results, should reduce dissolved VOC concentrations (including flux from back-diffusion) within 15 years.
- Relevant - Yes: eliminates offsite migration and potential impact to surface water body.
- Time-bound - Yes: 15 years.

Table 6-3 lists the absolute and functional objectives, along with a list of the SMART attributes of each functional objective. In this case, the vadose zone was addressed with previous remedial actions, and only saturated-zone impacts in the source and plume zones remain. The responsible party identified a specific and time-bound objective of MCLs within 15 years. Modeling results predicted that a remedy that rapidly eliminated mass flux from the source zone would not be sufficient (by itself) to collapse the plume zone within 15 years, thus both source-zone and plume-zone active remedies were required.

The modeling results were then used to develop a design that coupled an ISCO remedy in the source zone with a series of three ZVI permeable reactive barriers in the plume area. Modeling results based upon the assumption that groundwater passing through each barrier was reduced to MCLs (leaving back-diffusion of VOCs from the sorbed phase as the remaining source to plume-zone groundwater) provided predictions of long-term trends in groundwater VOC concentrations. As part of the performance and remedial progress evaluation, long-term groundwater monitoring results can be compared to these predicted trends to ensure that progress is being made towards the functional objectives. This comparison provided a SMART basis to evaluate remedy progress and to reevaluate the CSM and remedy.

6.5.2 Technology Screening

The bedrock at the site is characterized as metamorphosed schist and gneiss, with relatively low primary porosity or matrix storage. Saprolite and partially weathered rock also requires treatment, which influenced remedy selection but is not detaileded in this example. Although DNAPL is not observed in bedrock, elevated TCE concentrations indicate that a DNAPL phase is likely present. A plume of over 900 feet has emerged from the source area. Table 6-4 summarizes the initial screening of remedial technologies for the site based upon the type of bedrock present.

Table 6-4. Remediation technology screening matrix for fractured rock environments.

Click Here to view Table 6-4 in Adobe Acrobat format.

Technologies were selected on the following basis:

1. Among likely applicable physical technologies, air sparging was eliminated due to the need for extensive infrastructure construction (because much of the plume area extended off site with limited access), and surfactant flushing was eliminated because a separate phase DNAPL was never found in the fractured bedrock.
2. Among chemical/biological technologies, in situ bioremediation and monitored natural attenuation were eliminated due to relatively acidic groundwater conditions (pH approximately 5.2). Very little natural degradation of TCE was occurring, and estimates of pH buffering requirements to bring pH within a reasonable range were impractical.
3. Among ISCO and ISCR technologies, methods with long-lived reagents were desirable because the client no longer owned the facility, and access was limited.

Based on these considerations, ISCO and ISCR technologies with long-lived reagents were retained for detailed consideration.

6.5.3 Technology Selection

The technologies selected from screening-level assessment were ISCO and ISCR technologies using long-lived reagents. Conceptual modeling with REMChlor and PREMChlor was used for both the overburden and bedrock to assess the technology-independent remedial performance required to achieve the functional objectives. This effort indicated that the functional objectives could be achieved if:

1. The source area was rapidly eliminated with an aggressive technology.
2. Permeable treatment zones were constructed at accessible locations within the plume so that groundwater migrating through the barriers was treated to below MCLs. VOCs would diffuse (from matrix porosity and from the overlying saturated overburden) into groundwater, which would then encounter subsequent barriers.

Permanganate ISCO was selected for the source area. The permanganate was delivered with a solid slurry injection method. Injection in the bedrock interval targeted the existing fracture network. Transmissive, water-bearing fracture zones were identified by coring at each injection location. The following factors influenced remedy selection:

1. Large amounts (tons) of permanganate can be injected in a short period of time. The large volume was required to satisfy the natural oxidant demand as well as provide a slowly dissolving, long-lasting (years) source of oxidant to groundwater.
2. Permanganate exhibits a long lifetime in groundwater and can diffuse vertically from each lens to address the full range of fracture and matrix porosity. In fractured rock, permanganate can diffuse into the matrix porosity like the pathways followed by VOCs.

ISCR with ZVI was selected for the plume area. The ZVI was injected as a solid slurry. ZVI was selected rather than permanganate for the plume area because groundwater may discharge to an adjacent surface water body. The combination of technologies (ISCO in the source area with simultaneous application of ISCR in the downgradient plume area) required quantitative considerations of reagent transport, particularly of permanganate from the source area to the down gradient ZVI treatment zones.

1. A granular (rather than micro- or nanoscale) ZVI product was used because the granular ZVI would remain active for a long period of time (many years).
2. The long-lasting ZVI provides long-term treatment of VOCs desorbing and diffusing into groundwater from the rock matrix or from the overburden.

The approach used a wide variety of site characterization tools prior to remedial design. The remedial design included quantitative modeling coupled with bench and field pilot tests to confirm key assumptions. The full-scale implementation adopted a flexible approach that began with a design based on the CSM and available data, but was optimized on a boring-by-boring basis as core data and field observations became available.

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7 Monitoring

A groundwater monitoring strategy for fractured rock sites takes into account lessons learned during site characterization, and informational needs, including those unique to fractured rock, to help ensure that the selected remedy strategy attains site-specific cleanup goals. Monitoring strategies consider the following:

- the purpose for monitoring (compliance, operational or performance monitoring)
- the need to monitor groundwater and other media that may be important in understanding the fate and transport of contaminants in groundwater (such as soil gas)
- design of a monitoring well network
- development of a comprehensive monitoring plan that ultimately informs the practitioner whether remedial activities are on track towards attainment of site-specific cleanup goals.

7.1 Types of Monitoring

Monitoring is the collection and analysis of data (physical, water elevation, chemical, and biological) over sufficient time, locations, frequency to evaluate performance criteria. Successful monitoring is not a snapshot in time but rather, it defines and establishes trends in the parameters of interest, which relate to clearly defined functional objectives. For more guidance, see GSMC-1, Section 5.5 (ITRC 2013) and GRO-1, Section 3.5 (ITRC 2016).

Monitoring can be organized into three general types: compliance monitoring, operational (process) monitoring, and progress/performance monitoring. These monitoring types can overlap, and data can be collected to satisfy the requirements for two or more of the monitoring types. For example, water elevation data can be collected to satisfy all three monitoring types. Monitoring systems can be used to refine the CSM and optimize the number of samples and analyses required to measure compliance, operational process, and performance (see IDSS-1, Chapter 5 (ITRC 2011).

- *Compliance monitoring* is the collection of data to evaluate compliance with regulatory requirements and protection of human health and the environment.
- *Operational monitoring* collects data to assess whether a remediation system is meeting or approaching its functional objectives (ITRC 2011). This data is also used to identify, adjust, modify, and optimize remedial system performance.
- *Progress/Performance monitoring* is used to assess the effectiveness of a remedial approach in achieving functional objectives (ITRC 2011). Multiple lines of evidence are used to measure the effect remediation has on COC concentrations or mass discharge and the completeness of treatment. Effective performance monitoring allows decision makers to evaluate the soundness of functional objectives, determine the value of the remediation program, and determine if alterations to the remedial approach are required. Communicating the results of performance monitoring to the project stakeholders may be an effective way to keep them apprised of site progress—and may be required in some circumstances.

7.2 Media to Monitor

Contaminants found in fractured rock may partition into several different phases. These partitioned phases may consist of sorption to the aquifer matrix, vapor, groundwater, and surface water. Additionally, many other parameters or chemicals may be present that signify the processes occurring within the fractured rock. Therefore, it is important to consider all relevant phases while monitoring.

- *Subsurface gas*. Monitoring vapor constituents in subsurface gas can provide information regarding the migration and degradation of contaminants. As contaminants move through fractured rock or degrade, they may partition into vapors (gases). The movement within the subsurface is controlled by the fracture network. Migration patterns may differ from groundwater flow patterns.
- *Groundwater*. Groundwater is the primary transport media for dissolved contaminants at most sites. Contaminant transport is affected by contaminant partitioning to solid and gaseous phases and aquifer

hydrodynamics. Site-wide and regional/local groundwater elevation measurements, over time, provide insight on well integrity and changes to groundwater flow, which can be either natural or influenced by structures. Additionally, monitoring groundwater general chemistry may provide insight on the flow, changes occurring to the impacted zone, transport within the fractured media, and the interconnectedness of fractures.

- *Surface water*. Monitoring surface water is an extension of monitoring groundwater. Surface water includes seeps, springs, lakes, ponds, and other bodies of water. Monitoring surface water may indicate where groundwater is discharging to the surface or how surface water is affecting groundwater. Changes in surface water geochemistry may indicate changes in the impacted zone or in the transport of contaminants. Depending on the hydrologic environment, changes in surface water flow may be influenced by the degree of interaction between surface water and groundwater. This interaction can vary temporally and spatially, responding to changing surface water flow conditions (for example, a stream shifting between gaining or losing conditions.)
- *Aquifer matrix materials*. Typically, groundwater or subsurface vapor monitoring data are used as indicators of changed conditions in the aquifer matrix materials.

7.3 Monitoring Network Design

The design of a groundwater monitoring network in fractured rock can differ from that in unconsolidated media environments. A key element of monitoring system design is understanding temporal variations in chemical and physical conditions, whether natural or artificial changes. For example, remedial actions may change water elevations, which may alter groundwater flow direction. Fractured rock data requirements include: rock type, fracture network, and hydrogeochemical zoning.

The presence of a discrete fracture systems can also affect well construction and placement decisions. It is essential that wells used to monitor potential receptors are placed appropriately in three dimensions, given the fracture geometry. For some purposes, particularly performance monitoring, only wells that are required to meet the objectives need to be monitored. Wells installed to define the plume may, in later project phases, be redundant.

Many factors influence the shape of the impacted zone, including original source distribution, geology, hydrology, and biologic/abiotic processes.

7.3.1 Informational Needs for Designing Monitoring Well Network

Certain site-specific information is needed to design monitoring well networks, including but not limited to the following:

Rock Types

The particular rock types at the site can impact the temporal fate and transport of contaminants, which informs placement of monitoring wells as part of the network. The rock type may influence the potential for matrix storage and/or matrix flow. For example, the primary porosity in a granite and a sandstone are vastly different leading to differing monitoring network design. In can be expected that the temporal variations may be greater in a sandstone than a granite and more monitoring wells may be necessary.

Fracture Network

The placement of monitoring wells should rely on the mapped fracture network developed during the site characterization. Fractures may be discontinuous, may have variable orientations and apertures, may interconnect with other fracture systems, or may vary in other ways. Because of these variations, simply placing wells in the network based on an assumed, symmetrical two-dimensional plume geometry may not be meaningful. Well placement should be guided by the CSM to target discrete fracture zones. In addition, consider seasonal variations that occur in flow directions during times of greater regional pumping due to fracture orientation.

Hydrogeochemical Zoning

Hydrogeochemical zoning at a fractured rock site can also affect the design of a monitoring well network. The portion of the CSM that describes the geochemistry can guide the locations and depths of the monitoring wells. For example, rocks with high metal sulfide mineral content, such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), and galena (PbS), and cinnabar (HgS) can become oxidized and release metals into solution, thus generating acidity (as well as elevated aluminum, iron, and manganese). In this case, it may be desirable to monitor for pH and metals indirectly related to the contaminant release.

Other Media

Results from monitoring of other media such as vapor or surface water should be considered in the design of the monitoring well network. A subsurface gas survey indicating an area of elevated concentrations, that may not otherwise been included in the groundwater monitoring network, may suggest that an area is interconnected by fractures (although other causes such as utility conduits could be present). Guidance is available to assist in assessing subsurface gas (ITRC 2007, 2014; USEPA 2002a). Surface water impacts may also suggest an interconnectivity of fractures from the release area to the surface water body and should be considered in designing the groundwater monitoring well network.

Potential Receptors

The presence of potential environmental or human receptors is a significant consideration when designing a monitoring well network. Monitoring wells should be placed to evaluate the potential for exposure to receptors. For example, in fractured rock environments the migration pathways may vary temporally under a pumping scenario. For long-term monitoring programs, periodic reevaluation of potential pathways to receptors may be necessary.

7.3.2 Monitoring Locations

As with unconsolidated media, the locations of boreholes for a monitoring well network are identified using a more complete CSM. Placing boreholes prior to completing a robust CSM may result in an inadequate monitoring well network. A poorly designed well network can result in a less than optimal remediation strategy and may increase the costs and time frame required for remediation. Because drilling in bedrock can be expensive, boreholes and monitoring wells installed during site characterization or during any treatability testing may also be monitored and sampled as part of the routine monitoring program.

Multiple lines of evidence from the site characterization should be considered in placing monitoring wells, such as:

- fracture network
- groundwater gradient and direction
- geochemistry

An understanding of the fracture network in bedrock is foundational to making decisions regarding well placement. Results from site characterization can be used to map the fracture network to understand whether fracturing is dominated by horizontal (commonly bedding planes), vertical fractures (common for sedimentary rock) or by diagonal/multidirectional fractures (common for crystalline rock).

Once the fracture network is understood, hydraulic information about groundwater gradient, velocity, and flow direction within the fracture network aids in monitoring well placement. These considerations are particularly important when designing a program to monitor an injection-based remedy. Injected fluids are typically devoid of contaminants and until the injected fluid has migrated past the monitoring points, thus the evaluation of remedial performance cannot be considered reliable. If groundwater flow is slow or is slow in some of the fractures intercepted by a monitoring well, then the impact of this “uncontaminated” injected fluid can continue to affect the sample chemistry for years.

Understanding the noncontaminant geochemistry may aid in proper monitoring well placement. For example, if the contaminated fractures have high salinity and other fractures have low salinity, then salinity can be used to place wells and well screens across the same portion of the fracture network responsible for the fate and transport of the contaminants. The geochemical fingerprint of the source area contaminants can include a variety of low cost parameters that may predict future contaminant transport flow paths.

The locations of monitoring points share similarities to those in unconsolidated media, including:

- source zone wells
- impacted zone wells (analogous to plume wells for unconsolidated media)
- distal portions and boundaries of the area of impact
- cross-gradient wells
- sentinel wells
- surface water

7.3.2.1 Source Zone Wells

The source zone may be associated with the presence of DNAPL or LNAPL found within fractures, but for non-NAPL contaminants, may be simply associated with high contaminant concentrations occurring in fractures near the release area. In general, the source zone is the area with free product present, the release area, or both. Source zone contamination may be encountered in fractures, but can also be present in the matrix porosity, and in some cases, may occur as matrix flow.

Monitoring well installation within a fractured rock source area should allow monitoring of the desired metrics, but not result in spreading contaminants. A contingency plan should be developed prior to drilling that addresses what actions are necessary in the event a conduit that is spreading contaminants is discovered. The placement of monitoring wells should not cause further migration of contaminants, such as coring through the fractured rock and establishing a preferential flow path for otherwise immobile contaminants to reach groundwater. Appropriate drilling methods may be considered on a case-by-case basis that will allow drilling but prevent establishing preferential flow paths. Drilling should not create pathways between contaminated and uncontaminated fractures that are otherwise not impacted or hydraulically connected. In the event a conduit is discovered, the conduit must be sealed.

The shortest possible well screens or isolated intervals should intersect the impacted fractures of interest. This practice is important not only for preventing preferential pathways, but also for screening wells to provide the best possible discrete-interval samples. An alternative to short screen wells is long-interval wells that are separated into multiple hydraulically isolated zones with either inflatable packers or Flute systems. Long-interval wells can be new wells or legacy wells that may be repurposed. Multiple-zone wells offer valuable information and operational opportunities if they are constructed and maintained without allowing cross contamination or cross flows between separate fractures and portions of the fracture network.

Placing individual wells with access to multiple isolated intervals requires a team effort for planning and coordination, as well as on-site expertise and decision making. Strings of removable inflatable packers (inflated with compressed gas or with water) or FLUTe liners are installed as soon as possible after drilling and well logging are completed. Information from logs (especially caliper, televiewer, combined temperature-resistivity-gamma, heat-pulse flowmeter as possible) and water samples during or immediately after drilling can guide the selection of zone intervals and packer placement locations. Multiple-zone isolation systems of packers or FLUTe liners are reliable if properly sized, installed, and monitored for air or water pressure. Multiple-zone isolation systems of packers or FLUTe liners can be: (1) permanent; or (2) modular and be modified in configuration, or replaced if needed; or (3) converted in place from temporary to permanent.

High-value information and operational opportunities from individual wells with access to multiple isolated intervals include:

- 1D vertical profiles per well (and collectively providing 3D information in a volume of interest when several such wells are used) for water sampling, hydraulic heads, and monitoring prior to, during, after in situ remediation
- 3D characterization to determine or estimate hydraulic parameter distributions of both fractures and rock matrix, and fracture connectivity (hydraulic tomography and hydraulic tests at individual zones, tracer tests using multiple wells +/- multiple configurations)
- operational opportunities during remediation such as 3D in situ remediation with many possible configurations for simultaneous injection, withdrawal, hydraulic control, and monitoring using multiple zones in multiple wells

Alternative configurations of multiple individual single-zone wells cannot realistically provide the information and operational opportunities of wells with access to multiple isolated intervals each. The cost and logistics are prohibitive for a cluster of perhaps 4 to10 or more individual wells for every individual well with access to multiple isolated intervals.

7.3.2.2 Impacted Zone Wells

While the formal definition of a contaminant plume may not apply to fractured rock, the distribution of contaminants downgradient from the source area may be referred to as the impacted zone. This term refers to continuous fractures and fracture sets hydraulically downgradient from the source area that exhibit elevated concentrations of dissolved contaminants. Monitoring wells that are intended to be placed in the impacted zone are best placed using the current CSM.

Vertical characterization of the contaminant distribution in the fractures may be necessary to design a protective monitoring well network. For this characterization, long-interval wells that are separated into multiple hydraulically isolated zones with either inflatable packers or FLUTe systems may be considered as an alternative to short screen wells. Long-interval wells can be new wells or legacy wells that may be repurposed. The zones of highest contamination in the rock/fractures that present risk to off-site or downgradient receptors may need to be monitored.

7.3.2.3 Distal Portions or boundaries of the Area of Impact

Multilevel monitoring points typically are placed at the cross-gradient, downgradient, and vertical boundaries of the contaminant distribution, and between these boundaries and possible receptors. The placement of each monitoring point should account for the fracture flow network developed as part of the CSM. These wells also may be placed strategically to provide evidence determine whether contamination is crossing a compliance boundary. This determination may require sampling of fractures that are known to carry contaminants off site towards receptors; sometimes these pathways can only be found through discrete fracture characterization and sampling.

Multilevel monitoring generally should also be performed at any other compliance boundaries specified in remedy decision documents. Results from these monitoring locations may directly demonstrate unacceptable expansion of the contaminants distribution and changes in groundwater flow directions.

7.3.2.4 Upgradient and Cross-Gradient Wells

Upgradient and cross gradient wells may be useful as part of the monitoring well network to understand whether contamination is coming on-site from an up gradient source, or whether the impacted zone is spreading laterally. As with placement of other wells within the network, an understanding of the fractured rock hydrogeology is necessary to making decisions for placement of these wells.

Monitoring the groundwater geochemistry should include well locations where interconnected fractures are hydraulically upgradient and cross-gradient with respect to the area of impact. Assumptions concerning the geochemical setting and naturally occurring changes in geochemistry affect interpretation of data from the area of impact, so these assumptions should be tested and evaluated with other parts of the CSM.

As part of this evaluation, multiple monitoring points should be used to determine the variability of geochemical conditions outside the area of impact. Data concerning the movement of electron acceptors, donors, and any contaminants are used to determine whether the observed differences in geochemical parameter concentrations within the area of impact are due to contaminant transformation processes rather than natural variations in the background geochemical conditions. The locations cross-gradient to the area of impact help to evaluate changes in the area of impact geochemistry with time as groundwater migrates through uncontaminated fractured rock. Changes in geochemistry within the area of impact may not be directly related to attenuation of the contaminants, so geochemical changes outside this area generally should be assessed and compared to geochemical changes taking place within the area of impact. If upgradient and cross-gradient monitoring points show geochemical changes similar to changes in the area of impact, such changes may not be attributed solely to contaminant related processes (degradation) and may not serve as supporting evidence for degradation processes.

At some sites, monitoring groundwater elevations at locations in addition to those used for the monitoring chemical parameters may be needed to determine hydraulic gradients between hydraulically connected fractures. At these sites, appropriate locations for placing piezometers often include positions that are upgradient and cross-gradient to the area of impact, as well as in zones above and below the area of impact. Piezometers are usually spaced across the site so that groundwater elevation measurement errors are relatively small compared to the difference in groundwater elevations between piezometers.

7.3.2.5 Sentinel Wells

Sentinel wells may be installed to protect a potential sensitive receptor, or for a beneficial use. Monitoring wells for the monitoring network that are intended to be used as sentinel wells are best placed based on the current CSM—after gaining an understanding of the fractured rock hydrogeology.

7.3.2.6 Surface Water

Where surface water/groundwater interactions may be an important migration pathway, surface water bodies may need to be monitored as part of an effective monitoring system. At some sites, the CSM may include the potential connection between fracture systems and surface water bodies such as springs, rivers, ponds, or lakes. When considering monitoring in surface water bodies, be aware of seasonal hydrology that affects flow in these features.

7.3.3 Monitoring Well Design Considerations

Drilling into fractured rock is expensive compared to unconsolidated media so information gained from each drilling location should be optimized. This approach includes the optimal use of core holes drilled during site characterization. The monitoring network for a fractured rock site must be planned effectively and use as many of the existing boreholes and characterization data as possible. Because of the heterogeneous and anisotropic nature of fractured rock sites (for example, fracture orientation and discontinuities), there is inherent uncertainty about the fate and transport of contaminants. Therefore, the design of the monitoring network should be periodically reevaluated.

Monitoring well design considerations specific to fractured rock sites include selecting screen (or open borehole) lengths and positions that target transmissive fractures or zones, as well as evaluating flow conditions, evaluating potential hydraulic cross connections, and selecting appropriate well dimensions. Decisions regarding screen or open borehole lengths and depths of sampling intervals are based on the findings made during site characterization and remediation as described in the CSM.

Where the bedrock has adequate strength and competency, monitoring wells may be constructed as an open borehole. This approach can be more cost effective than placing filter pack and screen in the targeted zone. Using open boreholes provides flexibility in altering the well in the future by allowing for future deepening of the well, use of packers, and other options. Where open boreholes are used, well casing placement is essential to hydraulically isolate the targeted (open borehole) zone and eliminate the potential for cross-connections.

In some cases, existing wells that were not originally designed as monitoring wells are incorporated into monitoring systems. Prior to use, these wells should be assessed as to their potential for cross-connections of hydraulically distinct zones, using the appropriate characterization tools.

Discrete interval monitoring systems enable the monitoring of multiple depth zones in one borehole. These systems can reduce the high cost of drilling in bedrock. As when using open boreholes, care must be taken to eliminate or minimize cross-connections of hydraulically distinct zones. Discrete interval sampling technologies are described in Section 5.5.

The design of any monitoring well network at a fractured rock site should consider the potential for mobilizing contaminants or causing otherwise undesirable hydraulic cross connections. For example, otherwise immobile NAPL encountered in a bedding plane of a shale unit could be mobilized vertically through installation of a borehole that connects the impacted bedding plane to fractures or other bedding planes at other depths. As another example, a borehole drilled through an uncemented sandstone, where matrix flow provides the transport pathway for contaminants, could provide a pathway for vertical migration into otherwise unaffected fractures at other depths in the rock. The CSM should be used to design monitoring wells that minimize potential cross-connection

As at any site, the sampling interval or open borehole length for a given well is sized to obtain samples or take hydraulic measurements from the interval (set of hydraulically connected fractures) of interest. Fractured rock sites are unique in that the target monitoring interval is defined by fracture location, density, or orientation, as well as contaminant loading or geochemistry. The target intervals are based on the CSM, and factors to consider in determining screen interval length include the following:

- Match screen interval length to bedrock type, fracture density, continuity, or secondary porosity. In addition, consider geochemical values such as conductivity, contaminants, redox parameter and temperature.
- Interval depth and length are typically designed to target comparable intervals based on the CSM (such as sets of hydraulically connected fractures, or for a single fracture).
- Isolated intervals are matched to geochemistry to monitor fracture zones with a particular geochemical signature. Because attenuation of some contaminants is highly sensitive to the geochemical environment, it is often desirable to accurately identify and discretely sample locations in the area of impact where a particular geochemical condition prevails.

The design of the borehole and casing diameter are important considerations at fractured rock sites because of the potential need to isolate discrete zones. Well and borehole dimensions are driven by planned use of well casing and down hole packers, installation of discrete interval monitoring systems, and depth of the well.

7.4 Monitoring to Evaluate the Remedy

Starting with an end in mind is critical to effectively implementing a monitoring strategy. The USEPA guidance "*Groundwater Remedy Completion Strategy: Moving Forward with an End in Mind*", Section 6, describes four elements to an effective remedy evaluation (USEPA 2014):

- remedy operation
- remedy progress toward groundwater RAOs and associated clean up levels

- remedy attainment of RAOs and cleanup levels
- other site factors

The process outlined by USEPA is applicable to fractured rock sites as well as porous media sites and should be reviewed carefully before evaluating the performance of a site remedy.

USEPA further explains:

The evaluation of engineering, operating and monitoring components of a remedy should indicate whether the system is functioning adequately to achieve the RAO and associated cleanup levels and if remedy operation can be improved to reduce the remedial time frame.

7.5 Example of a Remediation Monitoring Strategy

USEPA's remedy evaluation structure has proven effective in the field. The case study for the Former Industrial Site in Greenville, South Carolina illustrates development of a remediation monitoring strategy. Table 7-1 summarizes the remedy evaluation structure for the site. Saprolitic overburden (both saturated and unsaturated) was also impacted and the subject of several phases of remediation. This discussion is focused only on the fractured rock zone.

Table 7-1. Remedy evaluation structure for the Former Industrial Site in Greenville, SC

Absolute Objective	SMART Functional Objective	Selected Remedy Component		Evaluation Questions	Metrics
Protect human health and the environment	Eliminate DNAPL and reduce groundwater VOC concentrations to MCLs within 15 years, to eliminate ongoing source of VOCS to plume area.	Source area in-situ chemical oxidation with potassium permanganate, injected as a solid slurry into water-bearing fracture zones.	Remedy Process Monitoring	Was permanganate reagent successfully injected in the target fracture zones, or was injection inhibited?	Comparison of actual injection rates, pressures, and volumes relative to design developed based upon preinjection CSM, as modified during implementation based upon field observations (distribution of water-bearing fractures) during drilling.
				Was the permanganate reagent mass injected commensurate with the matrix and contaminant oxidant demand?	
				Was there preferential flow into certain fractures?	
				Was reagent successfully distributed in the designed area of influence?	Visual observation (purple color) and geochemical characteristics (particularly oxidation-reduction potential) of groundwater in the treatment area.
				Is there evidence that injected reagent was preferentially directed away from the target treatment zone (i.e., daylighting, diversion to utility trenches, etc.), or towards downgradient areas?	Visual observations and geochemical characteristics of downgradient, sidegradient, and upgradient monitoring wells, and visual observations of surface, utilities, and other locations in the treatment area.
				Is there evidence of displacement of contaminants away from the source area as a result of injection?	Groundwater monitoring for contaminants outside the treatment area and comparison to pre-treatment data.
			Remedy Performance Monitoring	Do groundwater samples indicate sustained presence of permanganate?	Visual observation (purple color), geochemical characteristics (particularly oxidation-reduction potential), and contaminant concentrations in groundwater in the treatment area.
				Is there evidence of contaminant rebound?	
				Are contaminant concentrations decreasing as anticipated?	
				Does it appear that progress is being made towards the absolute objectives?	
			Remedy Attainment Evaluation	Are absolute and functional objectives achieved?	Contaminant concentrations in groundwater in the source and plume area.

Absolute Objective	SMART Functional Objective	Selected Remedy Component		Evaluation Questions	Metrics
Mitigate offsite migration of contaminants and potential impact to surface and groundwater resources	Reduce dissolved and sorbed-phase contaminant mass to MCLs within 15 years, to eliminate further offsite migration and potential surface water discharge.	In-situ chemical reduction utilizing granular zero valent iron, injected as a solid slurry into water-bearing fracture zones.	Remedy Process Monitoring	Was ZVI reagent successfully injected in the target fracture zones, or was injection inhibited?	Comparison of actual injection rates, pressures, and volumes relative to design developed based upon preinjection CSM, as modified during implementation based upon field observations (distribution of water-bearing fractures) during drilling.
				Was the ZVI reagent mass injected commensurate with groundwater reductant demand?	
				Was there preferential flow into certain fractures?	
				Was the reagent successfully distributed in the designed radius of influence?	Geochemical characteristics (particularly oxidationreduction potential) of groundwater in the treatment area, and contaminant concentrations downgradient of each barrier.
				Is there evidence that injected reagent was preferentially directed away from the target treatment zone (i.e., daylighting, diversion to utility trenches, etc.)?	Visual observations and geochemical characteristics of downgradient, sidegradient, and upgradient monitoring wells, and visual observations of surface, utilities, and other locations in the treatment area.
				Is there evidence of displacement of contaminants away from the treatment area as a result of injection?	Groundwater monitoring for contaminants outside the treatment area and comparison to pre-treatment data.
			Remedy Performance Monitoring	Do groundwater samples indicate sustained reactivity of ZVI?	Geochemical characteristics (particularly oxidationreduction potential), and contaminant concentrations in groundwater in the treatment area.
				Is there evidence of contaminant rebound?	
				Are contaminant concentrations decreasing as anticipated?	
				Does it appear that progress is being made towards the absolute objectives?	
			Remedy Attainment Evaluation	Are absolute and functional objectives achieved?	Contaminant concentrations in groundwater in the source and plume area.

7.5.1 Identification of Media to Monitor

The relevant media to monitor at this site are groundwater and surface water. Groundwater is the primary transport medium for contaminants, reagent, and geochemical conditions. The downgradient margin of the impacted zone is bounded by a perennial stream; thus surface water is a relevant media to monitor. Only the source area is overlain or adjacent to a building. The vadose zone in the source area (comprised of approximately 55 ft of dense saprolite) was remediated by other technologies, and postremediation indoor air monitoring confirmed there were no unacceptable risks, thus further vapor monitoring was not required.

7.5.2 Monitoring Network Design

Previous site investigations determined that the bedrock aquifer consists of a partially weathered rock zone at the interface between the rock and the overlying saprolite, which grades into competent bedrock over an approximately 10-foot interval. At some locations, the partially weathered rock and fractured interval is much thicker, approaching 100 feet. Fractures in the bedrock are predominantly subhorizontal. Water-bearing fracture zones could be readily identified and distinguished from mechanical fractures in bedrock cores by dark red to brown (oxidized iron) staining on the fracture surfaces. The crystalline rock is a metamorphic gneiss, with little matrix porosity.

An extensive network of 15 monitoring wells in the source area and 37 monitoring wells in the impacted zone and adjacent areas (including upgradient, cross gradient, and sentinel wells) provide a dense groundwater network of locations for data collection in both the saprolite and the bedrock (see site map in the full case study). The network includes wells with screens that intersect the saprolite interface and partially weathered rock interval, and deeper wells with screens only in the fractured bedrock interval. The preremedy well network was augmented during the remedy with additional locations just upgradient and downgradient of individual ZVI barriers to specifically monitor remedy progress. Additional wells on the cross-gradient margins of the impacted zone area were also installed to confirm the treatment area boundaries. Periodic surface water sampling is conducted, typically at up to four stations adjacent to the downgradient margin of the impacted zone.

7.5.3 Process Monitoring Strategy

The process monitoring plan focused on factors relevant to confirming that the field construction of the remedy matched the design of the remedy as closely as possible. Process monitoring of the injections in both the source and impacted zone centered primarily on the reagent distribution:

1. A design identifying specific well locations, injection depth intervals, and reagent volumes was developed based upon the CSM and site characterization data available prior to remedy implementation.
2. Each injection well was cored during drilling. This process allowed well-by-well evaluation of the fracture distribution, with ongoing updates to the CSM. This allowed adaptation of the remedy design to the observed fracture distribution at each location.
3. The amount of reagent injected at each targeted injection depth interval was monitored during injection. In some cases, multiple attempts were required to deliver the design reagent volume. In other instances, the target reagent volume could not be delivered, in which case the reagent was redistributed among other injection intervals in the same boring.

In the source area, the permanganate reagent colors the groundwater a distinct purple. Sampling of adjacent monitoring wells during injection visually confirmed distribution of permanganate during injection. The ZVI does not color the groundwater, so additional borings were needed after the initial field pilot tests to confirm the ZVI distribution.

7.5.4 Performance and Remedy Attainment Monitoring Strategy

Performance monitoring includes quarterly sampling for contaminants of concern and other analytes and parameters (such as redox, color, and manganese dioxide) used to evaluate the ongoing performance of the remedy and to identify locations that may require augmentation with additional reagent. The reagent is monitored quarterly. Monitoring locations include all the monitoring wells within, and adjacent to, the source and impacted zone treatment areas. This monitoring includes wells located cross-gradient of the treatment areas and downgradient sentinel wells.

In the source area, performance monitoring includes observations of color and presence of manganese dioxide, which are relevant to the long-term persistence of permanganate. The oxidation-reduction potential is a relevant parameter collected as part of low-flow sampling. The expected outcome is that permanganate is distributed throughout the source area and persists for several years. The permanganate was found to rapidly dissipate in some of the monitoring wells, and permanganate did not appear to reach other monitoring wells within the source area (allowing time for advection and diffusion of the reagent away from the initial emplacement zone). In response, additional injection around those locations was conducted to augment and optimize the remedy. In the impacted zone, the performance monitoring relies primarily on contaminant concentrations in groundwater downgradient of each ZVI barrier. The VOC data are compared with other groundwater characteristics that are associated with the ZVI, including oxidation-reduction potential and pH.

The initial remedial design was based in part on a modeling effort using REMChlor and PREMChlor. One output from these models includes a prediction of the contaminant concentrations at specific locations defined by the user. Thus, in addition to demonstrating steady progress towards the functional objectives, based upon declining contaminant concentrations, the remedy progress is also being compared with the REMChlor model predictions. Although reductions in contaminant concentrations are apparent, and the impacted zone appears to be contracting, the available period of post-remedy data is insufficient for a meaningful comparison. However, a strategy has been proposed to confirm long-term progress towards the objective. This strategy compares the modeled and measured contaminant concentration data, on a well-by-well basis, in order to identify locations or portions of the impacted area in which the remedy may require additional injection.

8 Modeling Fractured Rock

Groundwater flow and chemical transport models can help to characterize and remediate fractured rock sites at all scales. It is critical that any modeling be performed by modelers with experience in fractured rock, and with the specific application in fractured rock, because this modeling is significantly different from modeling in unconsolidated media. Models are tools that efficiently perform simple to complex calculations describing physical and chemical processes. A common tenet in modeling is that the overall value of a model depends on the quality of the input parameter values, and how well those parameter values reflect actual site conditions. This principle applies to modeling of fractured rock.

The complexity of fractured rock requires diligent focus on site characterization to develop data for the model. Although any model is an approximation, a well-designed model can help support decision making. Models, however, should not be considered as perfect predictors of future behavior. Based on initial model results and sensitivity analyses, specific data collection actions can be identified that further refine the model and further improve its usefulness.

Two types of goals often apply when using models:

- interpretive modeling to improve understanding of key processes or site characteristics, with the intent of improving the CSM or identifying significant data gaps for additional characterization
- predictive modeling to help with long-term site management, such as prediction of contaminant plume velocity or remediation timeframes with consideration of matrix diffusion or design of a hydraulic containment system.

Predictive modeling in fractured rock settings is difficult and is best suited to assisting the modeler in understanding various outcomes that may happen, rather than a definitive prediction of what will happen.

Applying a model requires simplifying the modeled setting by applying average input properties over some scale (such as site-wide) or identifying and simulating key major parameters in a more exact context (such as significant transmissive fractures). While most models incorporate simplified representations relative to the actual site complexity, they can be used to qualitatively or quantitatively evaluate site conditions or support remedial or corrective actions (MDEQ, Feb. 2014).

ASTM has compiled standards providing guidance on groundwater modeling. Many of the principles described in these standards are relevant to models of fractured rock systems (ASTM 1994, 1994b, 1994c, 1995a, 1995b, 1996, 1998).

8.1 Comparisons Between Modeling of Fractured Rock versus Unconsolidated Porous Media

Figure 1-1 illustrates some of the key similarities and differences between fractured rock and unconsolidated porous media. The factors shown in this figure have significant implications for groundwater flow and solute-transport modeling, and should be accounted for when considering or undertaking modeling of fractured rock sites. For example, using a standard soil porosity in an estimate of flow velocities in fractured rock can result in errors on the order of 1000%.

8.1.1 Groundwater Flow Modeling

Modeling of groundwater flow for water-balance purposes is similar in both types of media. Such models apply general representations of recharge and discharge boundaries, bulk hydraulic conductivity and storage parameters, and hydraulic stresses such as pumping wells. However, plan-view anisotropy may be more extreme in fractured rock than in porous media, particularly in situations with a dominant dipping fracture set. The SRSNE case study presents an example where the plan-view anisotropy was estimated as 1:20 in a system of dipping bedding-plane fractures; calibration of modeled particle-tracking results confirmed that the anisotropy estimate was reasonable. Also, in some cases, relatively discrete flow zones in fractured rock—such as fracture zones and faults—may require a finer model grid design in some parts of the model domain.

8.1.2 Solute Transport Modeling

Solute transport modeling in fractured rock is significantly different from modeling in unconsolidated porous media. Solute-transport models for unconsolidated deposits often use a bulk retardation factor to account for sorption-based retardation.

This approach does not apply in fractured rock because these models do not explicitly simulate the extreme hydraulic conductivity of fractures and do not explicitly simulate matrix diffusion.

Solute-transport models for fractured rock typically represent fractures as discrete flow zones and the unfractured matrix as a low-permeability, diffusion-dominated storage zone (such as in a dual-porosity formulation). Dual porosity formulations can capture the physics of transfer from flowing and storage zones; however the transfer coefficients are challenging to parameterize.

Characterizing fractured rock sites for modeling purposes should focus on fracture orientations and hydraulics (including hydraulic aperture estimation) and matrix storage capacity (such as porosity, bulk density, and organic carbon content). Solute transport modeling of metals also may require characterizing select geochemical parameters.

8.2 Types of Fractured Rock Models

An analytical model is typically a simple equation (often referred to as a scoping calculation), which may be easily applied using spreadsheet software. Analytical models are typically one-dimensional and offer a simplified or small-scale representation of site conditions. For example, one analytical model presents a simple solution for evaluating the diffusive flux into or out of a rock matrix (Parker 1994). Numerical models refer to the solution of more complex mathematical equations, which allow for representation of more sophisticated site conditions than is typically possible with an analytical solution.

A common historical modeling approach for fractured sites has been to use an equivalent porous media (EPM) framework. This approach assumes that the fractured system behavior is equivalent to porous media behavior and can be represented by an equivalent porous medium, with equivalent hydraulic conductivity in a certain area. EPM models do not directly account for preferential flow in fractures, but approximate the larger-scale conductivity of the fracture network, often with anisotropy in plan view and vertical perspective. EPM modeling approaches are useful in fractured rock settings for large-scale flow/water-balance assessment and capture-zone analysis for hydraulic containment systems. The applicability of EPM approaches is a function of scale, and increases with increasing scale. EPM approaches have even been demonstrated to be suitable for water resources management decisions in regional groundwater flow in karstic systems (Scanlon 2003).

Discrete fracture pathways and mass transfer between mobile (generally fractures) and immobile (generally matrix) porosities can be modeled with many hydrogeologic modeling codes; however the large degree of uncertainty in these parameters at most sites requires modeling to be performed in a stochastic or probabilistic framework and not as a single deterministic simulation. The level of accuracy and effort required for modeling depends on how well the selected numerical approach can be parameterized and discretized, given financial, technical, and schedule constraints (Selroos 2002). Modeling approaches that explicitly represent fractured rock systems include the Discrete Fracture Network (DFN) approach (Long 1983; Robinson 1984; Dershowitz 1985), the Hybrid Equivalent Porous Media (EPM)/DFN approach (Bordas 2005; Dershowitz 2006; Neuman 1987; Bruine 2003; ITRC 2003), and channel network (CN) approaches (Watanabe 1997). Reviews of these models and concepts can be found in the literature (Evans 1987; Haneberg 1999; Faybinshenko 2000; Berkowitz 2002; Selroos 2002; Dershowitz 2004; Ijiri 2009; ITRC 2003). DFN models are available through commercial, government, and academic sources, but are not used as commonly as equivalent porous media type models, even though DFN models offer advantages for modeling fractured rock systems.

8.3 Choosing the Right Model

To achieve modeling goals, it is critical to have well-defined and reasonable objectives for the modeling task, as well as the right model. Without a clear framework based on achievable objectives, modeling programs may not deliver the required results, may result in significant re-work, or may fail all together. The choice of a model to be used depends in a large part on the goals and specific objectives of the modeling. Table 8-1 presents some common objectives for modeling, and identifies suitable modeling approaches for each.

Table 8-1. Suitable modeling approaches for various objectives

Potential Model Objective	Potentially Suitable Approach
Estimating and tracking the possible migration pathway of groundwater contamination	DFN, EPM/DFN, CN

Potential Model Objective	Potentially Suitable Approach
Designing and evaluating hydraulic containment and pump-and-treat systems	Analytical, DFN, EPM, EPM/DFN, CN
Designing and evaluating groundwater monitoring networks	Analytical, DFN, EPM, EPM/DFN, CN
Estimating the possible fate and migration of contaminants for risk evaluation	DFN, EPM/DFN
Estimating contaminant removal rate and cleanup time	Analytical, DFN (with dual porosity), EPM/DFN (with dual porosity)
Evaluating the potential impact to downgradient receptors such surface water bodies or potable water supply wells	EPM with appropriate anisotropy coupled with particle tracking, DFN, EPM/DFN
Predicting contaminant concentrations for natural attenuation remedies	Analytical, DFN (with dual porosity), EPM/DFM (with dual porosity)
DFN – Discrete Fracture Network, EPM – Equivalent Porous Medium, CN – Channel Network	

The choice of a numerical modeling approach and the specific numerical model to use depends on the system to be modeled, the intended use of the model, available financial, human, and data resources, and the abilities and experience of the modeling team. The first and most crucial step in the process is to start at the end and identify what the goals of the modeling are and what decisions will be made based on the outcomes of the modeling project. Very different model choices (and approaches) would be made for goals such as designing a pump and treat system in a fault-dominated granite, versus designing a compliance monitoring network in a limestone, versus examining chemical process dependence for an injection-based remedy in an argillaceous setting.

A common mistake when performing fractured rock modeling is to choose an overly complex model or modeling approach under the assumption that it provides more versatility and flexibility during the process. The default approach should not be "What numerical code should I use?" but rather "Do I need to use a numerical model at all?"

Analyzing contaminant mitigation and designing remediation solutions need not be complicated—even at complex sites. It is often worthwhile and cost effective to use simple scoping calculations to determine the level of analysis necessary for a given objective. At sites having evidence that a single discrete pathway dominates transport, an approximate analysis to identify and quantify the pathway hydraulic properties may be sufficient to estimate transport behavior. At other sites, the most important process may be the exchange between fractures and matrix, rather than transport within the fractures themselves. In those cases, if the question to be answered involves time-dependent behavior at a site scale, an analytical solution of mass exchange might provide an excellent indication of the time scales of site remediation.

If numerical modeling is performed, the default approach should be to use the simplest tool for achieving project objectives. Increasing sophistication and capabilities in the model choice should be directly tied to the level of site complexity and the availability of data to support model design. Given the number of choices, the modeling team should consider the range of available approaches and their limitations and parameter requirements. All modeling requires simplifications, and fractured rock modeling often requires drastic simplifications as compared to modeling in typical porous media settings. ASTM (ASTM 1998) provides further details regarding groundwater model code selection.

8.4 Parameterization (Data Needs)

A full description of a fractured rock system would include data on the size, orientation and hydraulic properties of each fracture and matrix block, the temporal variability of hydraulic head through the system, the spatial variation in the permeability and porosity of the matrix, boundary conditions, sources and sinks of water and contaminants, geochemical understanding of the interaction of the rock and the contaminants, and much more. Collection of such detailed information is infeasible and often unnecessary. The more detailed the site characterization and the more it focuses on the key parameters for the modeling task, however, the greater the probability of meeting the modeling objectives.

A detailed discussion on the parameterization of models is outside the scope of this document, but many existing references are available on this topic (NRC 2015; NRC 1996). Key parameters that are likely to be needed for modeling fluid flow in fractured rock are listed below:

- Boundary conditions are required for every numerical groundwater flow model and some analytical models. These conditions are constraints on the mathematical model. ASTM (ASTM 1994b) provides guidance on assigning boundary conditions.
- Bulk rock hydraulic conductivity is required for models that focus on site-scale water-balance analysis, capture-zone estimation, and generalized groundwater flow directions. These parameters can be measured using field hydraulic tests at wells and boreholes.
- Bulk rock anisotropy data is needed for the same purposes as above; these can be estimated based on multiwell pumping test analysis, resistivity survey data, seismic refraction data, fracture set orientations, or calibrating particle tracking results to match observed tracer or plume migration directions.
- Fracture set orientations are used to help estimate the potential for anisotropy and probable direction of dominant fluid flow.
- Fracture apertures and fracture porosity data are used to simulate or calculate fluid flow rates and simulate particle-track velocities.
- Hydraulic heads and gradients are needed for a variety of modeling purposes.

In addition to those listed above, key parameters for modeling solute transport in fractured rock include the following:

- Matrix permeability helps to interpret whether flow in the matrix needs to be explicitly simulated to represent solute transport with a reasonable degree of representativeness. If the matrix permeability is very low, mass transfer into and out of the matrix can be represented as diffusion.
- Matrix porosity and bulk density are needed, and if the solutes of interest are organic compounds, the matrix organic carbon content is also required.
- Geochemical parameters are used to simulate reactions that can affect mobility of metals and the viable degradation pathways of organics.
- Biologic parameters such as microbial populations support the conceptual model and simulation of degradation pathways for organics.
- Solute degradation half-life data are needed when simulating a reactive solute.

When possible, these parameters should be characterized within the dominant pathways, zones, or strata where flow and mass flux occur.

A particularly powerful use of models is to help identify areas of CSM uncertainty and sensitive parameters that may warrant further characterization. Model results may indicate areas of poor performance (calibration or prediction), where additional data may help reduce uncertainty or improve model estimations. The CSM (and translated numerical framework) is then updated based on the additional data, and the model run to assess the improved performance. Using models in this manner can help focuses field investigations, reduces the overall costs of site characterization, and improves confidence in the evolving CSM.

8.5 Model Calibration, Sensitivity Analysis, and Uncertainty

A thorough treatment of model calibration, sensitivity analysis, and assessment of uncertainty in fractured rock settings is beyond the scope of this document. An overview of these topics is provided here, however, so that modelers and the ultimate end-users of modeling can understand general approaches and limitations. For more information, refer to a modeling textbook such as *Applied Groundwater Modeling* (Anderson and R. Tokar 2015) and ASTM documents.

8.5.1 Model Calibration

Calibration is the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater flow system (ASTM 1994, 1995a, 1995b, 1996). Examples of hydrologic model calibrations at fractured rock sites include studies of potential sites for high level nuclear waste repositories such as Yucca Mountain (Zyvoloski 2003) (Mazurek 2003).

Some aspects of model calibration that are unique to fractured rock settings as compared to porous media include:

- *Potential for extreme heterogeneity*. Fracture zones, faults, or (in the case of carbonate rock or volcanics) karst-like conduits are likely to have hydraulic properties that differ extremely from those of the overall rock mass. If so, these types of features may need to be explicitly simulated to achieve a reasonable degree of agreement with measured site data.

- *Anisotropy* – Fractured rock may contain aligned fracture sets, which can impart a high degree of anisotropy to the hydraulic conductivity field, including in the horizontal and vertical planes. The SRSNE case study presents an example in which the plan-view anisotropy was estimated as 1:20 in a system of dipping bedding-plane fractures; calibration of modeled particle-tracking results confirmed that the anisotropy estimate was reasonable.
- *Low storativity*. Groundwater elevations in fractured rock settings can change quickly by significant magnitudes because of the low storativity of fractured rock formations, so that steady state model calibration may require collection and averaging of numerous water level measurements at calibration target wells.
- *Dual domain mass transfer and storage*. It may be necessary to explicitly simulate matrix diffusion effects rather than using bulk sorption-based retardation approximations.

Calibration can be performed by trial and error, or with the aid of an automated parameter estimation code such as PEST or UCODE. The preferred approach to develop reasonable model inputs in the calibration process is as follows:

1. Identify reasonable ranges of input parameters.
2. Run predictive models within an automated parameter estimation framework, using various combinations of input parameters within the pre-defined ranges.
3. Identify the model input parameter combinations that produce output that is most consistent with site-specific observations and measurements.

Data used typically for model calibration targets include heads, measured flow rates, particle tracking of simulated groundwater flow directions (for comparison with mapped plume morphology), and geochemical measurements under natural and pumped conditions. Model input parameters are adjusted and model outputs are compared to site-specific measurements. Model results are then compared statistically to determine the relative degree of difference between the model output and site-specific measurements.

Parameter estimation codes are mathematically complex and require a highly skilled and experienced modeler; uninformed use of this approach can lead to incorrect interpretations. Many combinations of input parameters may yield output that is a good fit to observed conditions. A good fit, however, does not necessarily ensure that the model correctly represents the flow and transport conditions. Best practices include calibration to transient data or for a minimum of two different stress regimes (such as pumping and static conditions, or wet and dry seasons).

8.5.2 Sensitivity Analysis

Sensitivity analysis is a quantitative evaluation of the impact of variability or uncertainty in model inputs on the degree of calibration of a model and on its results or conclusions (Anderson 1992; ASTM 1994b). Sensitivity analysis in fractured rock settings generally progresses as it does in porous media. For several key types of input parameters, the input parameters are adjusted within a reasonable range of values and the model results are compared to the calibrated model in terms of the magnitude of changes to model calibration statistics. Input parameters selected for adjustment during sensitivity analysis are often those that have potentially large ranges in magnitude (such as hydraulic conductivity) or have not been well constrained by site-specific data (such as recharge, anisotropy values, or timing of contamination releases). Input parameters that are more sensitive produce larger changes in model results; those that are less sensitive produce smaller changes in model results. In this process, the modeler may find that a particular sensitivity run produces better calibration statistics than the previously identified calibrated model. If so, then the modeler may choose to replace the previously considered calibrated model with the revised model setup.

Analysis of the problem with initial scoping calculations often reveals ways to simplify numerical models. For example, some numerical model inputs have little effect on output. Quantitatively analyzing the sensitivity—or in this case, the insensitivity—of a model can be powerful because it can reveal what additional data may or may not constrain a model parameter and decrease model uncertainty. This type of insight is more valuable than that resulting from a single numerical model calculation.

8.5.3 Assessment of Model Uncertainty

Model uncertainty can arise from the following sources (NRC 2015):

- simplifications necessary to implement a conceptual model in a numerical model
- limitations of the understanding or implementation of physical-chemical-biological processes in the model
- errors in the numerical model implementation

- limitations in the match between measurements and model results

Quantifying these errors and uncertainties, to the extent possible, helps ensure that numerical models and the conclusions drawn from them are appropriately applied. Presentation and use of results from numerical models in fractured rock should be explicitly linked to the known uncertainties. Except for the simplest cases, providing an indication of the uncertainty in the model estimates, through methods such as box and whisker plots, provides the end user with an important understanding of the reliability and ultimate usefulness of the estimates.

Model uncertainty can be assessed in parallel with sensitivity analysis. However, uncertainty assessment often focuses on predictive model simulations, where hydraulic stresses or parameters are adjusted to reflect a hypothetical future condition (such as the operation of extraction wells, installation of hydraulic barriers, or removal of a constant-concentration source). In uncertainty analysis, the results are compared before and after model input parameter adjustment to identify the degree of change in model results, and therefore the degree in model uncertainty, associated with that parameter change.

Just as examining the sensitivity of a model to input parameters can guide subsequent model development, so can quantifying the uncertainties that arise during the modeling process guide interpretation of model output. Structural uncertainties (fracture locations, size, and orientation) can be large and are often the most difficult to quantify and estimate when modeling fractured rock (NRC 2015). Formal statistical data analysis methods can be used to place bounds and characterize parameter distributions (normal, log normal) through statistical analysis of the data, if enough data are available. When data are limited, use experienced-based expert opinion with sound, documented explanations for the choices made.

8.6 Limitations

Models are conceptual descriptions, or approximations, that describe physical systems through the use of mathematical equations. Models are not exact descriptions of physical systems or processes. The applicability, or usefulness, of a model depends on how closely the mathematical equations approximate the physical system being modeled. For this reason, models that are based on a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations produce better predictions (Michigan Department of Environmental Quality 2014).

9 Stakeholder Perspectives

9.1 Economy and Long-Term Resource Protection Concerns

Improved characterization of fractured rock leads to more appropriate remedial decisions and reduces the damage to precious groundwater resources if these decisions are properly applied. The same concern for indoor air, surface water and direct contact hazards should be addressed through appropriate remedial decisions. Restoring as much of the resource as possible as a stakeholder priority is important. Minimizing the loss will help to guarantee groundwater resources and other resources will continue to be available for future generations.

Protecting drinking water, surface water, sediments, and air quality fall under regulatory programs that require permits to access these resources in an environmentally safe and sustainable way. The practice of obtaining a permit to access a resource implies that the resource will be sustainable and usable for economic development, drinking water, agriculture, fisheries and wildlife, and in some cases air quality. Minimizing loss of any of these resources as a result of contamination needs to be a component of every remedial design. Stakeholders must identify this as a concern when dealing with remedial options at sites in their communities or tribal lands.

Poor remedial decisions, based upon limited data, can place tremendous long-term economic burdens on communities due to loss of property values, development potential, institutional restrictions on aquifers, and the undesirable reality that the community must face with respect to long-term contamination under their city or individual properties. Often, the aesthetic quality of the aquifer is diminished on a long-term basis downgradient of these contaminated sites, which essentially makes the aquifer useless for domestic water supplies and much more expensive to treat for municipal water supplies. These treatment costs are often passed on to the individual property owner and the community. Use of monitored natural attenuation, if not applied properly at these fractured rock sites, can lead to some of the undesirable conditions.

This fractured rock characterization approach promotes a better conceptual model of the site allowing a more focused and potentially a less costly feasibility study and remedial design process. Better definition of the source area and extent of contamination trapped in the fractures and diffused into the rock will save time and cost when designing effective remedial options. If these processes are applied properly, they should immediately reduce risk and long-term remediation costs normally incurred with remedies that often proceed with little or no source control. Stakeholders often support this approach to minimize the loss of groundwater through failed remedies and institutional controls, which also reduces the economic loss of development potential of large tracts of land in communities.

9.2 Stakeholder Views Regarding Remedial Decisions

This guidance outlines an approach that can provide enough information to determine if an existing remedy is protective of human health and the environment. This approach can also determine whether long-term monetary resources are being wasted on a remedy that would operate better if source control were implemented, for instance, or for a multitude of other cost saving issues identified during investigation. Stakeholders support this approach when objectively presented and tied to remedial actions objectives that restore aquifers, protect future groundwater resources, and reduce risk to human health and the environment.

Public and private sector funds should be focused on returning resources to a useful and economically productive status. The current regulatory model of restricting resource use and access to resources (institutional controls) can be a long-term stigma to the community and may prevent the return of community prosperity. Protecting human health and the environment goes hand-in-hand with economic viability and community prosperity. There is no need to sacrifice either of these goals to achieve a cost-effective and successful remedy. Reduction and hydraulic control of the plume to a small area that cannot be quickly cleaned up due to fractures and diffusion into the rock may also be an outcome where return to drinking water criterion appears not to be possible. Long-term control and minimizing the foot print of the restricted access to groundwater is a key consideration when implementing a successful and acceptable remedy.

9.3 Stakeholder and Tribal Acceptance

Remedies that were crafted without the understanding and characterization of fractures and the bedrock system have removed groundwater resources from current and future generations un-necessarily in many instances. Stakeholders have been skeptical at many sites because of inadequate characterization and extensive use of risk-based decision making to justify large-scale, long-term natural attenuation remedies for aquifers. The characterization and decision making at complex fractured rock sites has been viewed as expensive and difficult for remedial design. Better identifying where the contamination resides in the aquifers fractures and how much is diffused into the rock matrix should lead to better designs that can address these difficult problems.

10 Regulatory Challenges

Although many regulators are receptive to advanced site characterization information and newer characterization tools, some may not be comfortable with the departure from standard site characterization practices. For regulatory agency personnel who have been operating under what may now be considered outdated CSMs for subsurface contamination, there is a clear challenge to incorporate the newer views of contaminant behavior in fractured rock systems into ongoing cleanups. This chapter discusses some of the potential regulatory acceptance issues associated with the fractured rock site characterization methods. Issues include understanding new tools and technologies used to develop a more representative CSM, the types of analyses, decisions, and responses associated with the various types of data collection (which vary depending on site and project circumstances), and reconciling the advancements in site characterization with current regulatory expectations and requirements.

10.1 Measuring Groundwater Flow Rate and Direction

Regulations are developed to cover a wide range of situations. Regulations intended to prevent a particular problem from occurring may impede characterization and remediation efforts. An example of one such rule is Minnesota Rule 4725.2050. Use of Wells or Borings for Disposal or Injection Prohibited:

> A well or boring must not be used for disposal or injection of surface water, groundwater, or any other liquid, gas, or chemical, except for groundwater thermal exchange devices, drilling fluids, vertical turbine prelubrication water, treatment chemicals, priming water, water used for hydrofracturing, and water used for disinfection in accordance with parts 4725.1831, 4725.2950, 4725.3250, 4725.3725, 4725.5050, 4725.5475, and 4725.5550.

Compliance with this rule prevents the injection of dye-tracing chemicals, nutrients, organisms, or other materials for groundwater contamination remediation in a well or boring. However, the regulatory authority may grant a variance to the rule for these purposes in certain circumstances.

There are also situations when regulations are prescriptive or were written at a time when the complexities associated with fractured rock groundwater flow and contaminant transport were not well understood or addressed. In these situations, meeting the regulatory requirements and technical needs of a project can be contradictory. An example is the following requirement, which is cited in the California Code of Regulations for RCR-Permitted sites (Title 22, section 66264.97):

> In addition to the water quality sampling conducted pursuant to the requirements of this article, the owner or operator shall measure the water level in each well and determine groundwater flow rate and direction in the uppermost aquifer and in any zones of perched water and in any additional aquifers monitored pursuant to subsection (b)(1) of this section at least quarterly, including the times of expected highest and lowest elevations of the water levels in the wells.

This requirement, like others around the nation, does not account for the complexities of fracture flow and contaminant transport. In this specific example, groundwater flow rates and directions simply calculated from water levels from wells at a fractured rock site, as required, could result in directions and rates that are not accurate. Although regulatory requirements need to be met, the usefulness of the results from meeting these requirements should always be considered and documented, especially when meeting the requirements create results that are inaccurate or inconsistent with the CSM.

10.2 Design of the Investigation

Regulatory actions typically start when regulators are notified of the presence of contamination. This is usually the result of either real estate transactions or other discovery of contaminants, often in drinking water wells. The design of the initial investigations is often based on traditional investigations that likely have not been designed using the principles described in this guidance. Regulators must decide how to use the data provided and may not have the authority to, for example, require monitoring wells to be redrilled if the screen monitored interval is not likely to be representative of the fractured rock condition.

10.3 Investigation and Monitoring Well Design

Monitoring well design may be constrained by regulatory guidance requiring specific screen vertical interval lengths (such as10 feet), and well spacing intervals (often up to 500 feet). Conventionally, solid waste programs have interpreted USEPA guidance indicating wells should be spaced no more than 500 feet apart as not allowing regulators to routinely require more closely spaced wells, even when there may be good fracture-based reasons for requiring wells in some areas of a facility to be much more closely spaced and others to be more widely spaced.

Existing drinking water wells can be potential contaminant flow pathways. Most environmental regulators are unlikely to have the authority to require such wells to be closed or modified, and health departments that may have that authority may be reluctant to require drinking water well closure or modification unless an alternate water supply is available. Bedrock well construction and closure may be under the authority of a separate entity and closure requirements may not adequately prevent contaminant migration. For example, Virginia Department of Health requirements for well closure currently only specify that bedrock wells closed in rock below the groundwater table be backfilled “with clean fill” to the water table and grouted or bentonite filled until five feet from the surface. Furthermore, some states have requirements for drinking water well construction that may be applied to monitoring wells. For example, requirements for well casings to be constructed to particular depths, or particular depths into bedrock, may appear to restrict construction of monitoring wells at the upper bedrock transition zone that is often a significant zone of groundwater movement and storage.

The regulatory process typically requires samples to be taken at regular time intervals. This approach may not allow samples to be taken at the most high risk times (such as during high rainfall or low rainfall periods) and may not reflect the relatively rapid groundwater and contaminant flow velocity in some fractured rock aquifers.

10.4 Protecting Multiple Flow Zones in Fractured Aquifers

Characterizing a site across confining layers may be subject to state rules that may prohibit the interconnection of aquifers and have specific definitions of what is considered confining layer in bedrock and unconsolidated materials. The interconnection of wells or borings completed in different aquifers through piping manifolds or other means, such as with a flexible liner, may be prohibited. In these cases, the local regulatory authority may require wells or borings through a confining layer to have an outer casing driven or grouted into the confining layer and an inner casing installed through the confining layers with the annular space filled with grout. It is important to work closely with the local regulatory authority and understand rules that may affect the characterization procedures.

Issues may arise because an alternative to short screen wells with one monitoring zone per well is long-interval wells that are separated into multiple hydraulically isolated zones with either inflatable packers or FLUTe liner systems. These multiple-zone wells offer valuable information and operational opportunities (described below) if they are constructed and maintained without allowing cross contamination or cross flows between separate fractures and portions of the fracture network. Emplacement of individual wells with access to multiple isolated intervals requires a team effort for planning, coordination, and on-site expertise and decision-making. Appropriate drilling (+/- coring) methods may be considered on a case-by-case basis that allow drilling but prevent establishing preferential flow paths.

Strings of removable inflatable packers (inflated with compressed gas or with water) or FLUTe liners are installed as soon as possible after drilling and well logging are completed. Information from logs (especially caliper, televiewer, combined temperature-resistivity-gamma, heat-pulse flow meter) and water samples during or immediately after drilling, guide the selection of zone intervals and packer placement locations. Multiple-zone isolation systems of packers or FLUTe liners are known to be reliable if properly sized, installed, and monitored for air or water pressure. Multiple-zone isolation systems of packers or FLUTe liners can be (1) permanent; (2) modular and thus modified in configuration, or replaced if needed; or (3) converted in place from temporary to permanent.

High value information and operational opportunities from individual wells with access to multiple isolated intervals include:

- Information can be obtained, such as 1D vertical profiles per well (and collectively providing 3D information in a volume of interest when several such wells are used) for water sampling, hydraulic head measurements, and periodic monitoring prior to, during and after in situ remediation. 3D characterization can also be obtained to determine or estimate hydraulic parameter distributions of both fractures and rock matrix, and fracture connectivity (hydraulic tomography, and/or hydraulic tests at individual zones, and tracer tests using multiple wells +/- multiple configurations). Local rules may prohibit the injection of dye tracing materials, organisms, nutrients or oxidation compounds, but in certain circumstances a variance from the rules may be granted.

- Operational opportunities available during remediation include 3D in situ remediation with many possible configurations for simultaneous injection, withdrawal, hydraulic control, and monitoring using multiple zones in multiple wells.

Alternative configurations of multiple individual single-zone wells cannot realistically provide the information and operational opportunities of wells with access to multiple isolated intervals each because of the cost and logistics of having a cluster of perhaps 4 to10 or more individual wells for every individual well with access to multiple isolated intervals.

10.5 Decision making

Regulations have traditionally been written based on an understanding that data are taken from grab samples, either or soil or rock, or from relatively long-screen monitoring wells. For example, in petroleum programs, corrective action requires removal of free product to a thickness of 0.01 feet or the maximum extent practicable. Regulations may not allow flexibility in addressing data from samples taken from discrete sample intervals, or from specific intervals in a core sample that may be elevated compared to a groundwater sample averaged over a longer interval.

10.6 Stakeholders

Most state environmental agencies have been designated by legislatures as the entity tasked with protecting the citizen's interests related to environmental protection and contamination. While some states have specific processes to form and engage independent stakeholder groups actively in remediation decisions, many do not. Most regulatory programs have specific processes for citizens to comment on active cases and help regulators make better decisions, but the authority for those decisions still lies with the regulatory agency. Regulators might find it helpful to offer guidance on how best to engage stakeholders specifically for fractured rock sites (for example, guidance on how best to present a CSM and discuss uncertainty).

11 Case Studies

Three detailed case studies are presented in this chapter. In addition to these detailed case studies, a selection of other relevant case studies are summarized in the Case Study Matrix. The Case Study Matrix is divided into case studies that illustrate investigative tools and those that illustrate selected remedial technologies applied within the last 10 years or so. The selection of these case studies was not based on a particular vendor product or service. Also, these case studies represent a snapshot of applied solutions, but are not representative of all potential technologies or strategies that have been applied.

For fractured rock the remedial technologies selected may be driven by the degree of back- diffusion from matrix porosity and the physical characteristics and particular hydraulics of the he site. The remedial strategies represented in the Case Study Matrix include approaches such as:

- push-pull (extract, amend, and reinject)
- gravity injection
- slurry injection/fracturing
- permeable reactive barrier
- recirculation.

When the list of technologies used is differentiated by rock types, the distribution changes somewhat. Thermal technologies are frequently selected for treatment of sedimentary rock but are seldom selected for crystalline (igneous and metamorphic) rocks. ISCO and bioremediation are frequently selected for treatment of crystalline rocks.

Note that successful results are reported at many sites where limited characterization was performed and where the monitoring well networks may also be limited. For fractured rock, characterization to understand the rock types present and the architecture of fracture networks (particularly which fractures play a larger role in the hydraulics or fate and transport of contaminants) is critical for successful remediation. A complicated and expensive characterization is not always necessary, but for each site there is an appropriate level of characterization that supports the following decisions:

- whether the CSM is sufficiently robust to proceed to remedy strategy selection
- which remedial strategy to use
- which design basis and detailed design elements (including performance assessment details) to use to reach site-specific remedial goals and objectives

11.1 Former Industrial Site, Greenville, South Carolina

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Special challenges at this site include:

- *15-acre plume area with limited access*
- *very little natural degradation*
- *high groundwater VOC concentration*
- *dual-zone aquifer in saprolite and fractured bedrock*

Technologies initially applied include:

- *removal and SVE for unsaturated soil*
- *thermal desorption in source area*
- *groundwater pump & treat*

Technologies applied to optimize and improve remedial effectiveness include:

- *permanganate solid slurry injection for ISCO in source area*
- *ZVI solid slurry injection for ISCR in plume area*

Site Description

The site is a former electronics manufacturing facility that used TCE for glass cleaning. An estimated 1,365 gallons of TCE were lost between construction in 1991 and discovery of the release in 1996. TCE use was terminated in 2000. The site is under new ownership and is now used for warehouse and light industrial purposes. The facility and source area lie near the top of a hill, with limited access to the plume area due to the steep slope, a major highway, and a heavily forested area.

Lithology/Bedrock Description

The site is underlain by saprolite that grades into competent bedrock. The saprolite is heavily oxidized, relatively low permeability silt, sand, and clay, with varying degrees of relict bedrock structures and quartz veining. The transition from saprolite to competent rock is a partially weathered rock zone that is visually similar to the saprolite but marked by greater density and more abundant rock fragments. The upper bedrock exhibits varying degrees of fracturing and weathered zones in a matrix of mica schist and gneiss, feldspar gneiss, and granite. The depth to rock ranges from approximately 90 feet below grade in the source area, to as shallow as 6 feet in the plume area.

Hydrogeology

The water table occurs in both saprolite and in bedrock where depth to rock is relatively shallow. Depth to groundwater ranges from approximately 55 feet below grade in the source area to as shallow as approximately 5 feet in the plume area. Slug and permeability tests yield an average hydraulic conductivity of 3.0×10^{-4} fpm in the saprolite and 1.5×10^{-3} fpm in the partially-weathered rock. Bedrock transmissivity estimates from yield tests range from 1.5×10^{-3} ft^2/min to 5.5×10^{-2} ft^2/min. The piezometric surface and groundwater VOC isoconcentration maps indicate a partially radial flow pattern from the source area between a northwest bearing and a southern bearing, consistent with the hill topography. Downgradient of the source area, the groundwater flow direction is primarily to the south and southwest following the regional flow regime towards a local river adjacent to the site.

Contaminant Nature and Extent

The primary contaminant found at the site is TCE, at concentrations historically ranging as high as 1,200 mg/L in the source area. Cis-1,2-dichloroethene and vinyl chloride are also present at maximum concentrations as high as 15 mg/L and 0.53 mg/L, respectively. In general, little TCE degradation is occurring, and both cis-1,2-dichloroethene and vinyl chloride are often not detectable. Overall plume area is approximately 15 acres, with a maximum length (measured along the axis of highest TCE concentration) of approximately 1,000 feet.

Site Characterization

Site characterization was complicated by the two-zone aquifer system, with flow in both the relatively low-permeability saprolite and partially-weathered rock, and in fractured rock. Objectives included refining potential transport pathways and confirming plume boundaries.

Site Characterization Approach/Tools

Since investigations began in 1996, site characterization has been conducted in multiple phases and has used traditional monitoring wells and a range of additional tools. Direct-push and hand-auger soil sampling was conducted where possible to delineate shallow soil. Traditional hollow-stem auger drilling was used in the saprolite. Air, mud rotary, and core drilling were used in the bedrock. FLUTe liner was used for DNAPL screening. Discrete interval sampling tools, passive diffusion bags, and HydraSleeve samplers were used primarily to provide vertical delineation in the source area. Passive diffusion bags were also used for an instream assessment. Summa canisters and Dräger tubes were deployed for indoor air and soil vapor characterization. Screening-level grab groundwater samples were collected during sonic drilling of wells for reagent injection using the Isoflow discrete-interval sampling system developed by Boart Longyear.

Results of Site Characterization

The additional characterization effort associated with implementing the pilot and full-scale remedies resulted in better vertical and horizontal delineation of the plume to focus and refine costs. One significant observation was the variability of the partially-weathered rock zone that separates the saprolite from the underlying competent bedrock. This transitional zone ranged from virtually absent, to as thick as approximately 50 feet. The variability in thickness coupled with higher hydraulic conductivity relative to the saprolite affected groundwater flow pathways at the saprolite-bedrock interface.

Remedial Approach

The TCE tank and appurtenances were removed in 2001, along with 140 tons of soil. An interim SVE system was operated in the source area excavation from 2002 to 2006. Groundwater extraction and treatment from two wells adjacent to the source area and two wells in the proximal plume area (at the property boundary) began in December 2006. Extraction in the source area was discontinued in early 2007, and an in situ thermal desorption system was operated in the source area from January to June 2007. The estimated TCE mass removed over the course of these activities was approximately 13,875 lbs and an estimated 2,900 lbs (based upon difference from the estimated TCE volume lost) remained in the ground.

These technologies achieved the remediation goal for the unsaturated soil, significant mass removal in the source area, and mitigating further off-site plume migration. Rebound of groundwater TCE concentration in the source area and the residual concentrations following these actions did not meet the overall site remediation goals. An unsuccessful pH adjustment pilot test was conducted as part of a bioremediation assessment in 2009. Subsequently, a design was developed that coupled permanganate in situ chemical oxidation in the source area with ZVI in situ chemical reduction in the plume area. Permanganate offered rapid mass removal in the source, while ZVI emplaced as multiple barriers in accessible locations offered a long-term solution to address slowly desorbing VOC mass in the plume area.

The remedies required quantitative design considerations and modeling, including:

- Develop remedial designs that have a reasonable likelihood of achieving MCLs within 15 years.
- Develop and refine methods to inject solid slurries of permanganate and ZVI, in low-permeability saprolite and in fractured bedrock.
- Ensure effective distribution of each reagent sufficient to achieve design goals, including vertical and horizontal injection spacing and reagent mass.
- Mitigate potential downgradient transport of permanganate into the ZVI barriers.
- Adapt site management to allow for design modification based upon field observations during implementation.

Field pilot tests of ZVI in the plume area and permanganate in the source area were conducted in 2011. Borings were advanced immediately after the injection to assess physical reagent distribution, and groundwater was monitored for two years following the pilot. Based upon the pilot test results, a full-scale design was implemented in 2013.

A total of 83 tons of potassium permanganate blended with sand was injected via 87 discrete vertical intervals in 14 injection wells over the course of the pilot and full-scale ISCO remedial action. A total of 725 tons of ZVI was injected via 368 discrete vertical intervals in 62 injection wells in three barriers across the plume, over the course of the pilot and full-scale ZVI remedial action. The full-scale remedial actions were conducted from July 2013 to July 2014. An additional 5,208 gallons of 5.3% sodium permanganate solution was injected by gravity feed at two well locations in September 2015 to address a small portion of the site that was not effectively treated during the full-scale injection.

Performance

Source area results for TCE are summarized graphically in Figure 11-1. The baseline represents the condition prior to the 2011 pilot test. Overall groundwater TCE concentrations (through January 2016) have been reduced by ≥99.9% in 12 of 15 monitoring wells, and at 99.4%, 99.0%, and 73.8% in the remaining three wells. The poorest performance (73.8% reduction) is in a well located within the former tank excavation, and reflects rebound following >99.9% removal immediately after the remedial action. Additional sodium permanganate injection is planned for this location.

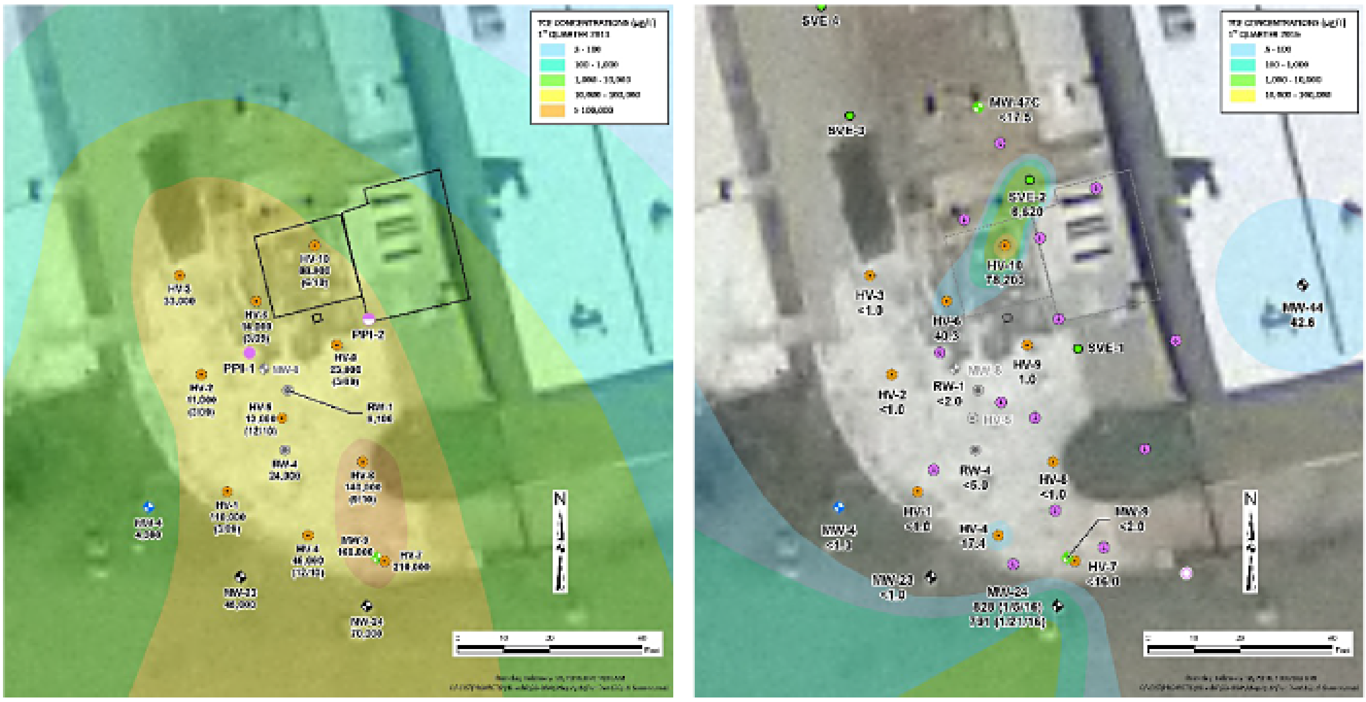

Figure 11-1. Source area results.

Plume area TCE results are summarized graphically in Figure 11-2. The core of the plume (TCE >10,000 mg/L and maximum of 96,000 mg/L) has contracted significantly, with remaining TCE concentrations ≤2,230 mg/L. Results for MW-33, the plume monitoring well exhibiting the highest baseline TCE concentration, have been reduced by 99.2% from a maximum of 110,000 mg/L one week after the field pilot test in May 2011 to 905 mg/L in the latest sampling event (January 2016) (Figure11-3). The concentration of cis-1,2-dichloroethene (formed as an intermediate degradation product from TCE) exhibited initial increases from the baseline (<2,000 mg/L) to a maximum of 43,000 mg/L, and have subsequently degraded to 1,650 mg/L.

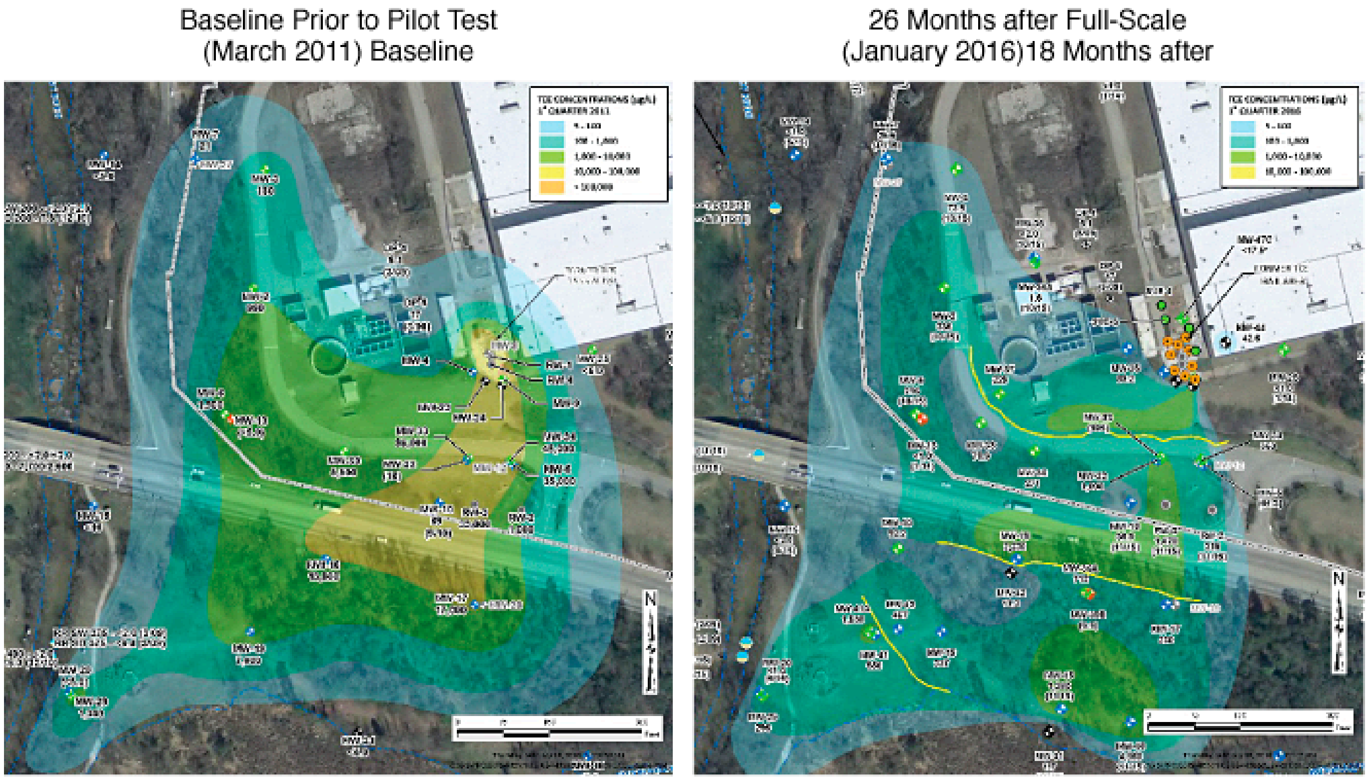

Figure 11-2. Plume area results.

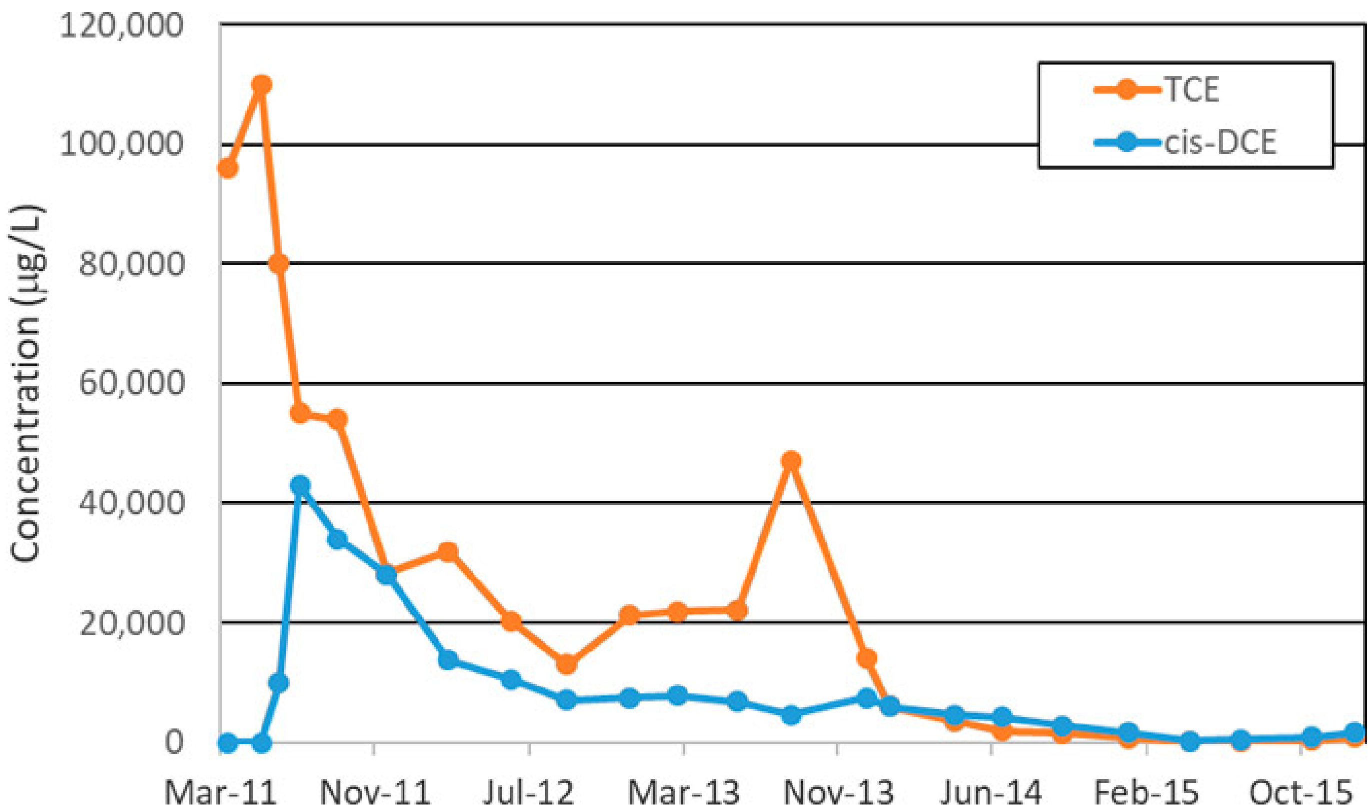

Figure 11-3. MW-33 TCE and cis-DCE Results.

Remedy Evaluation

The overall remedial evaluation, implementation, modification, and performance assessment for the remedial actions since 2011 (the permanganate ISCO and ZVI remedial actions) were developed based upon guidance in the Integrated DNAPL Site

Strategy document (ITRC 2011). Remedial evaluation began with an assessment of remedial objectives. The absolute objective was to restore the overburden and bedrock aquifer to drinking water standards. Functional objectives were developed based upon a monitoring program to ensure progress, coupled with evaluation to assess if additional remedial action was required. The absolute and functional objectives were SMART: ***s****pecific* (achieve MCLs in groundwater), ***m****easurable* (groundwater VOC analyses), ***a****ttainable* (based upon modeling predictions and aggressive remediation), ***r****elevant* (meeting drinking water standards to restore groundwater quality), and ***t****ime-bound* (within 15 years).

The evaluation began with REMChlor and PREMChlor modeling. Plume contraction and decay estimates were developed utilizing site-specific hydrologic, geologic, and VOC data coupled with various source and plume remediation scenarios to determine what levels of VOC mass and flux reductions across the site were likely to achieve the absolute objective within 15 years. Source area remediation coupled with three reactive barriers spanning different zones within the plume area were likely to achieve the objectives. Specific technologies were then evaluated and designed to achieve those reductions, as outlined in the previous sections. Additional site characterization data were collected to refine the conceptual site model, including vertical delineation of VOC concentrations and monitoring well installation to address data gaps relevant to design assumptions.

Pilot test results were used to optimize the full-scale remedial design. Procedures were developed to assess field observations and results daily to continuously refine the site conceptual model and to optimize the design to match site conditions during construction. Ongoing remedy performance and progress towards (or achievement of) the functional and absolute objectives are evaluated with an extensive groundwater monitoring program. Additional injections have been conducted based upon the results to address small areas exhibiting rebound and requiring further treatment.

Costs

Costs are available for the permanganate and ZVI pilot tests and full-scale remedial construction, and estimates of associated monitoring and reporting costs from 2011 through 2015. The field pilot test cost was $590,655 including the reagents, labor, and equipment for drilling, injection, and reporting. Associated sampling, lab analytical, permitting, engineering, project management and other routine costs are estimated to be an additional 25%, for a total cost of approximately $740,000 for the field pilot test. The full-scale construction cost was $4,579,729 including the reagents, labor, and equipment for drilling, injection, and reporting. Associated sampling, lab analytical, permitting, engineering, project management, client oversight and other routine costs are estimated to be an additional 20%, for a total cost of approximately $5.5 million for the full-scale implementation including performance monitoring and reporting.

Outcomes and Challenges

The large plume area, limited plume access, concentrated source area, and dual-zone (saprolite/bedrock) aquifer system pose special challenges. Results to date have generally met expectations based upon the REMChlor and PREMChlor modeling predictions with respect to source and plume concentration reductions. A few locations in the source area have required additional injection to address rebound, and plume-area monitoring well locations located distally from the ZVI barriers have not yet exhibited reductions because sufficient time (relative to transport velocity) has not passed. Permanganate breakthrough from the source area to one boring location in the closest ZVI barrier has been observed in the latest sampling events.

Lessons Learned

Remedial designs and objectives are often based on differentiation between overburden and bedrock with little consideration of the transition zone between these regions. A valuable lesson learned at this site was the importance of the partially weathered rock transition zone between saprolite and bedrock. This zone exhibits significant vertical and lateral variability and has a hydraulic conductivity that averages about one order of magnitude higher than the saprolite. The variability required ongoing assessment and remedial design modification during construction.

11.2 Solvents Recovery Service of New England, Inc., Superfund Site, Southington, Connecticut

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Key Concepts

- *Connection between technical questions, data needs and collection methods*
- *Economical measurement of average hydraulic apertures of fractures*
- *Drilling with dye to improve screening-level groundwater sample quality*
- *Horizontal anisotropy assessment in dipping fracture system*
- *Deep DNAPL zone delineation in bedrock*
- *Evaluating fracture apertures versus depth*
- *Use of groundwater flow and solute-transport modeling (with matrix diffusion) to select monitoring well locations, interpret the bedrock NAPL-zone and VOC plume extent, and confirm no completed exposure pathway*

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Site Description

The Solvents Recovery Service of New England, Inc., (SRSNE) Superfund Site is in Southington, Connecticut, approximately 15 miles southwest of the city of Hartford (United States Environmental Protection Agency [USEPA] Region 1). SRSNE processed more than 100 million gallons of solvents, fuels, paints, and other organic liquids between 1955 and 1991. Still bottom discharges to lagoons and other releases produced a nonaqueous phase liquid (NAPL) source zone and associated aqueous-phase plumes in overburden and fractured bedrock. The plumes of volatile organic compounds (VOCs) above drinking-water standards have been hydraulically controlled by pump and treat since 1998. The site has been intensively studied for the past 35 years.

Physical Setting

The site is in the Quinnipiac River Valley, which is part of the Connecticut Valley Lowland that occupies a regional, structural rift basin with tilted bedrock strata (Figure 11-4). The area is characterized by relatively broad river valleys separated by low north-northeast trending bedrock ridges. The former SRSNE Operations Area is at the base of the eastward sloping hill. The adjacent properties to the east and southeast are in the flat, central part of the river valley. The Quinnipiac River flows south through the study area.

Overburden Geology. The overburden includes Pleistocene glacial outwash and a thin, discontinuous layer of till at the bedrock surface, with isolated deposits of fill and post-glacial alluvium. The overburden thickness varies throughout the study area, from approximately 15 to 30 fft at the SRSNE Operations Area, 50 ft at the Quinnipiac River, and up to 200 ft east of Queen Street. The overburden gradually coarsens and its hydraulic conductivity increases southward within the river valley from approximately 1 to 10 ft/d near the Operations Area to over 1,000 ft/d at a distance of approximately 2,000 ft south of the former Operations Area.

Bedrock Geology. The bedrock consists of the Upper Triassic New Haven Arkose "red beds" (Rogers 1985) see Figure 11-4. Bedrock fractures in the region dip moderately to the east-southeast, parallel to the bedding (Hubert 1978; Rogers 1985; Blasland 1998). Steeply dipping fractures, however, have also been observed in outcrops near the site, and in core samples and downhole fracture-logging results within the study area. While normal faults have been mapped approximately 2.5 miles west and 2.0 miles east of the site (Rogers 1985), no bedrock faults have been reported within the Remedial Investigation (RI) Study Area.

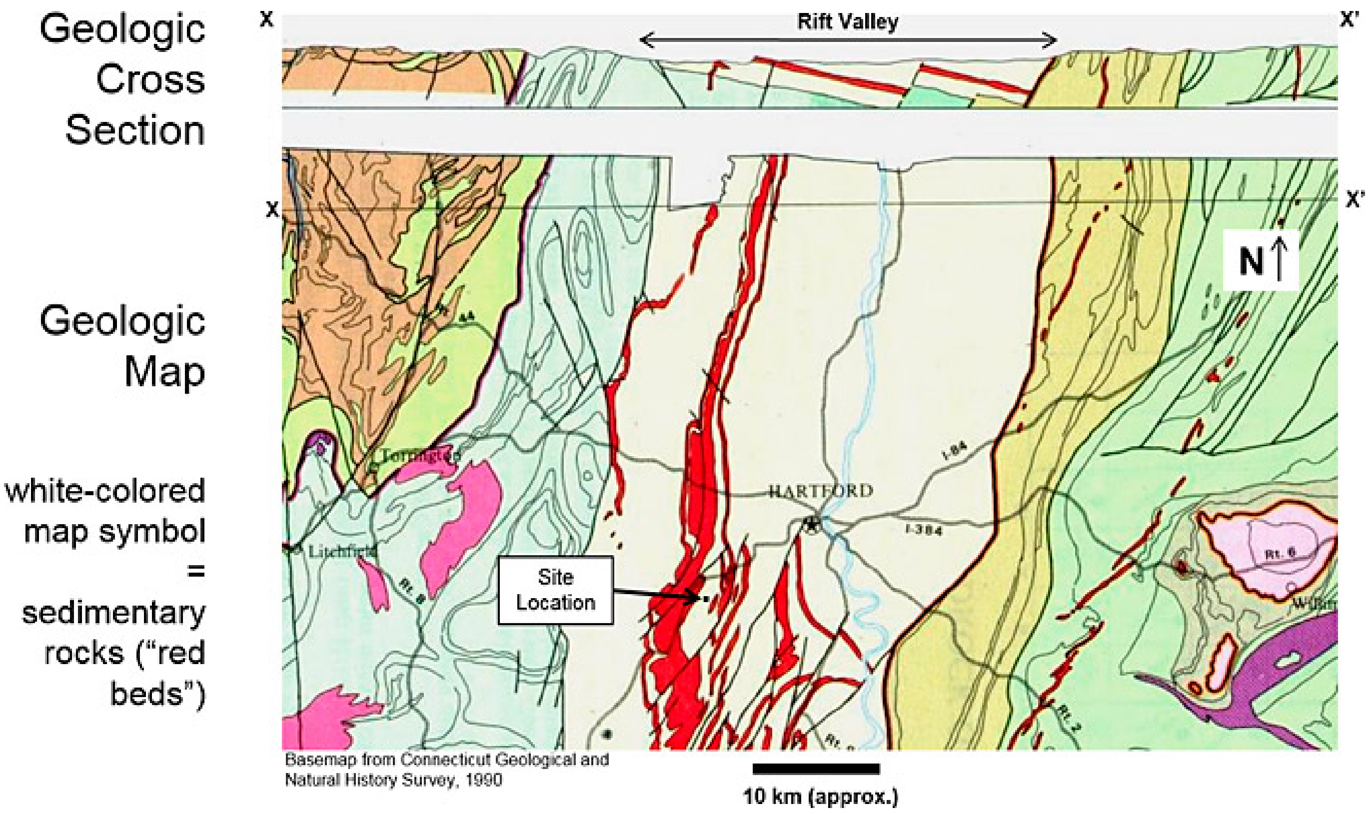

Figure 11-4. Portion of Connecticut bedrock geologic map.

Bedrock Investigations

Bedrock investigation methods at the SRSNE Site are summarized with pink shading in Table 11-1. Each data-gathering step was linked to one or more classes of data needs/uses and collection methods. Investigations included the following:

- optical and/or acoustic televiewer logging of fracture orientations and spacing.
- fracture orientation stereonet plots (such as those in Figure 11-5).
- rock core sampling and laboratory analysis of matrix parameters that affect VOC solute transport (porosity, bulk density, organic carbon content).
- fracture aperture calculations – the average hydraulic aperture in 41 borehole intervals was calculated as $b = C (K_b S)^{1/3}$, where b is the average hydraulic aperture (cm), K_b is the interval bulk hydraulic conductivity (cm/sec), S is the average fracture spacing in the interval, which is the total interval length divided by the number of fractures in the interval (cm). This equation is based on Zeigler's work (Zeigler 1976). The constant C accounts

for gravity and water viscosity, and is equal to 0.0543 at 10°C, the representative groundwater temperature at the site.

- vertical profiling of bedrock boreholes prior to installing wells in deep bedrock boreholes.

Table 11-1. Matrix of data needs and data collection methods

Fractured Bedrock Assessment Data Needs		Nature and Extent	Fate and Transport		
		NAPL/GW plume delineation	NAPL/GW flow direction	NAPL/GW flow velocity	Dissolved plume velocity
Bulk rock	rock type				
	minerology				b (inorganic COCs)
	permeability			e	e
Fracture data	orientation	d or f	d or f	d or f	d or f
	depth			b or d	b or d
	spacing			b or d	b or d
	aperture*				e and (b or d)
	porosity*				e and (b or d)
	permeability			e and (b or d)	e and (b or d)
Matrix data	porosity				c
	bulk density				c
	foc (TOC)				c
	permeability				
Hydraulic data	water table depth	a	a	a	a
	gradients	a	a	a	a
COC data	types	a			a
	3-D distribution	a	a (NAPL)	a (NAPL)	a
	conc. trends				a
	chem./phys. properties		a (NAPL)	a (NAPL)	a
Other					COC half life

Notes:

1. Indicated methods are required or recommended under most normal circumstances. (exceptions will arise)
2. Letters are coded to type of investigation activities, as follows:
   a - standard investigation methods
   b - core sampling and inspection
   c - core sample lab analysis
   d - downhole fracture logging
   e - packer test(s) or single-well test(s)
   f - lineament and/or outcrop assessment
3. * Fracture aperture and porosity can also be obtained from logging borehole flow with and without pumping
4. COC = constituents of concern
   GW = groundwater
   NAPL = non-aqueous-phase liquid
   TOC = total organic carbon

At four deep bedrock boreholes drilled to depths of at least 200 ft below ground surface (bgs), extraction packer tests were performed at 20-foot intervals to measure hydraulic conductivity and collect screening-level groundwater samples for VOC analysis. To help ensure that drilling water was adequately purged from the surrounding fractures before sampling, fluorescein was added to the drill water and monitored during purging (McCaughey IN PRESS).

To help avoid dense NAPL (DNAPL) remobilization, the bedrock DNAPL zone was investigated using a “DNAPL Contingency Plan” prepared by Dr. Bernard Kueper, Ph.D., P.Eng., of Queens’s University.

Bedrock Characteristics

Lithology. The bedrock in the study area is the New Haven Arkose (Rogers 1985), which consists of red to reddish-brown to pink, interbedded sandy to silty channel deposits and silty floodplain sediments deposited in a rift setting known as the Hartford Basin (Fritts 1963; Hubert 1978); also see Figure 11-4).

Bulk hydraulic conductivity. The geometric mean hydraulic conductivity from specific-capacity tests at 69 bedrock monitoring wells is approximately 0.2 ft/day. The range is 0.001 to 27 ft/day.

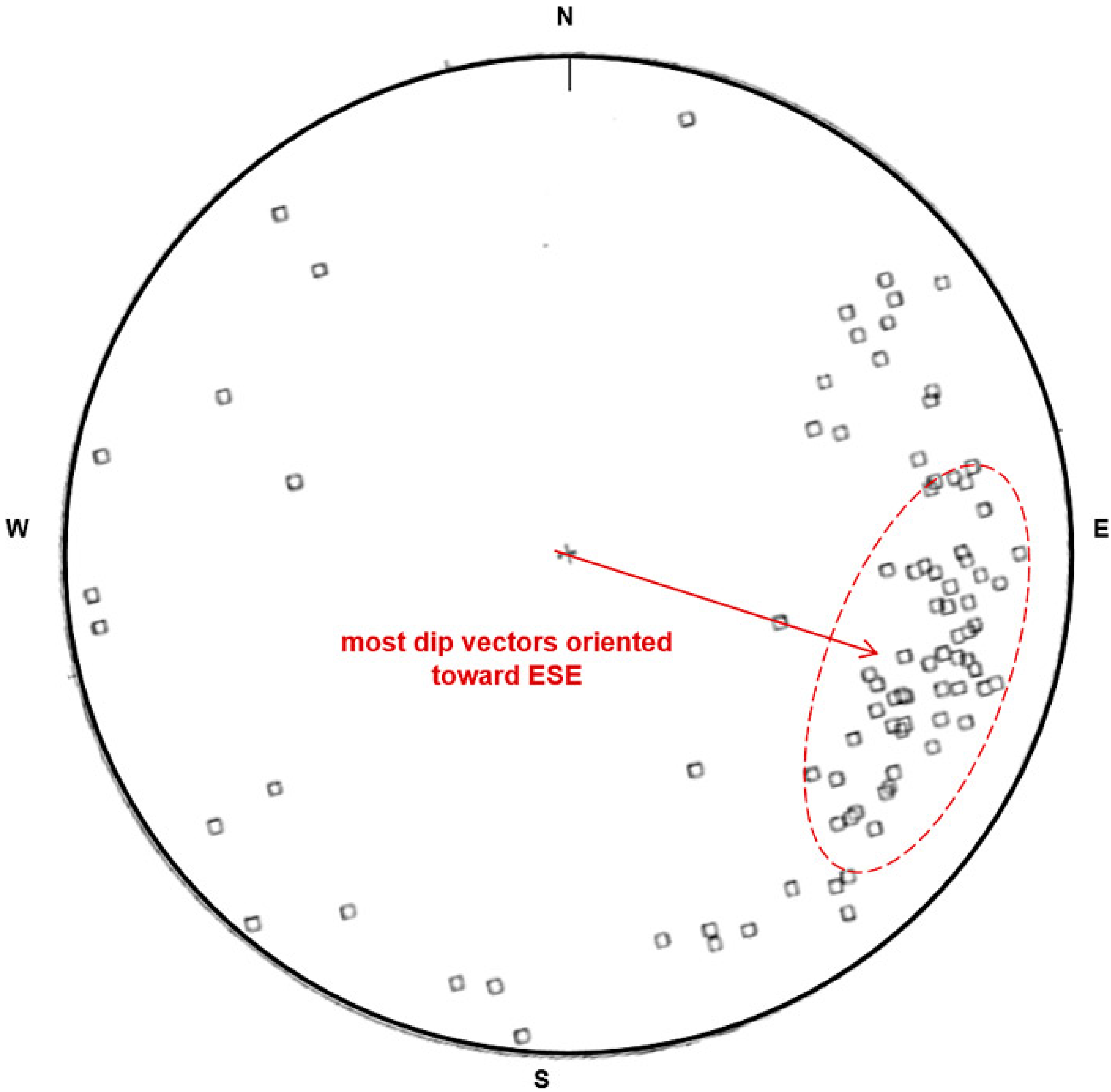

Figure 11-5. Equal area stereonet of measured fracture dip vectors.

Fracture orientations, hydraulic apertures, spacing and hydraulic conductivity. Based on Borehole Image Processing System (BIPS) data collected at three deep bedrock holes during the RI(for the 94 fractures observed in these boreholes the mean dip direction was 107.53 degrees (east-southeast) and the mean dip angle was 22.06 degrees (Figure 11-5). Most of the fractures observed via BIPS and in core samples paralleled bedding. Based on the numbers of fractures and hydraulic conductivity values for 41 injection and extraction packer-test intervals, the mean fracture aperture and spacing are 0.0097 centimeters (cm) (97 microns) and 155 cm, respectively. The fraction of the entire bedrock volume occupied by fractures, meaning the "fracture porosity", equals the mean aperture divided by the mean spacing, or 6.3×10^{-5} (0.0063 %). The mean bedrock fracture has a hydraulic conductivity of approximately 7×10^{-1} cm/sec, or 2,000 ft/day.

Matrix porosity, bulk density, fraction of organic carbon and permeability. Laboratory analysis of 18 core samples during the RI indicated that the unfractured matrix of the bedrock has an average porosity of 7.7%, bulk density of 2.52 grams/cubic cm, and fraction of organic carbon (f_{oc}) of 0.0049. The ratio of matrix porosity to fracture porosity shows that the matrix has over 1,000 times more storage capacity than the fracture system for dissolved solutes. The mean matrix permeability was measured as 4.2×10^{-7} cm/sec, or 0.00011 ft/day, indicating that VOC mass transfer to and from the matrix occurs mostly by diffusion rather than advection. The matrix data provided a means to account for VOC sorption in the matrix in solute transport modeling.

Bedrock Groundwater Hydraulics

Generalized Groundwater Flow Directions. Groundwater in the overburden and bedrock converges toward the Quinnipiac River from the east and the west, and generally has a southward component consistent with the southerly slope of the valley. Based on hydraulic heads measured at 227 wells, piezometers, and surface-water measurement points within the RI Study Area, nearly all overburden and bedrock groundwater within the monitored depth discharges to the Quinnipiac River. The exception is groundwater extracted by plume containment wells. As bedrock groundwater migrates southward, it also rises into the overburden. Long-term hydrographs at pairs of shallow and deep bedrock wells indicated vertical hydraulic connection within the bedrock.

Hydraulic Conductivity Across Bedding. The bedrock hydraulic conductivity perpendicular to the plane of bedding was estimated based on the drawdown responses at observation wells during pumping at individual specific capacity test wells. Neuman-Witherspoon analysis (Sen 1989) suggested that the vertical to horizontal anisotropy of the bedrock is approximately 1:200.

Plan-View Anisotropy Due to Dipping Fractures. The plan view anisotropy of the bedrock was estimated using the equation (Anderson 1992):

$$K_x/K_y = R/[1 - (1 - R)\cos^2 A]$$

where:

K_x = horizontal hydraulic conductivity parallel to the strike of bedding plane fractures

K_y = horizontal hydraulic conductivity in the dip direction

R = hydraulic conductivity perpendicular to bedding (K_p)

$K_{b\,=}$ hydraulic conductivity in the plane of bedding

A = dip of bedding.

Taking the calculated vertical to horizontal anisotropy of 1:200 as a rough approximation for R and using the dip angle of approximately 20^0, the estimated a plan view anisotropy of K_x / K_y is approximately 1/20.

A regional MODFLOW model was developed to help design hydraulic containment systems for the VOC plumes in the overburden and bedrock. Initially the bedrock layers were assigned equal horizontal K values in both model grid directions ($K_x = K_y$). The model calibrated closely to measured hydraulic heads, but the bedrock particle tracks calculated by MODPATH paralleled the hydraulic gradient toward the east-southeast, which did not match the elongate shape of the VOC plume toward the south. After changing the plan view anisotropy to the calculated value of K_x/K_y = 1/20, the model was still well-calibrated to hydraulic heads and the MODPATH particle tracks reasonably matched the shape of the bedrock VOC plume. In applying the calculated 1/20 plan view anisotropy, the product of K_x and K_y was held constant. Note the angle between the hydraulic gradient and the particle tracks with arrows (Figure 11-6).

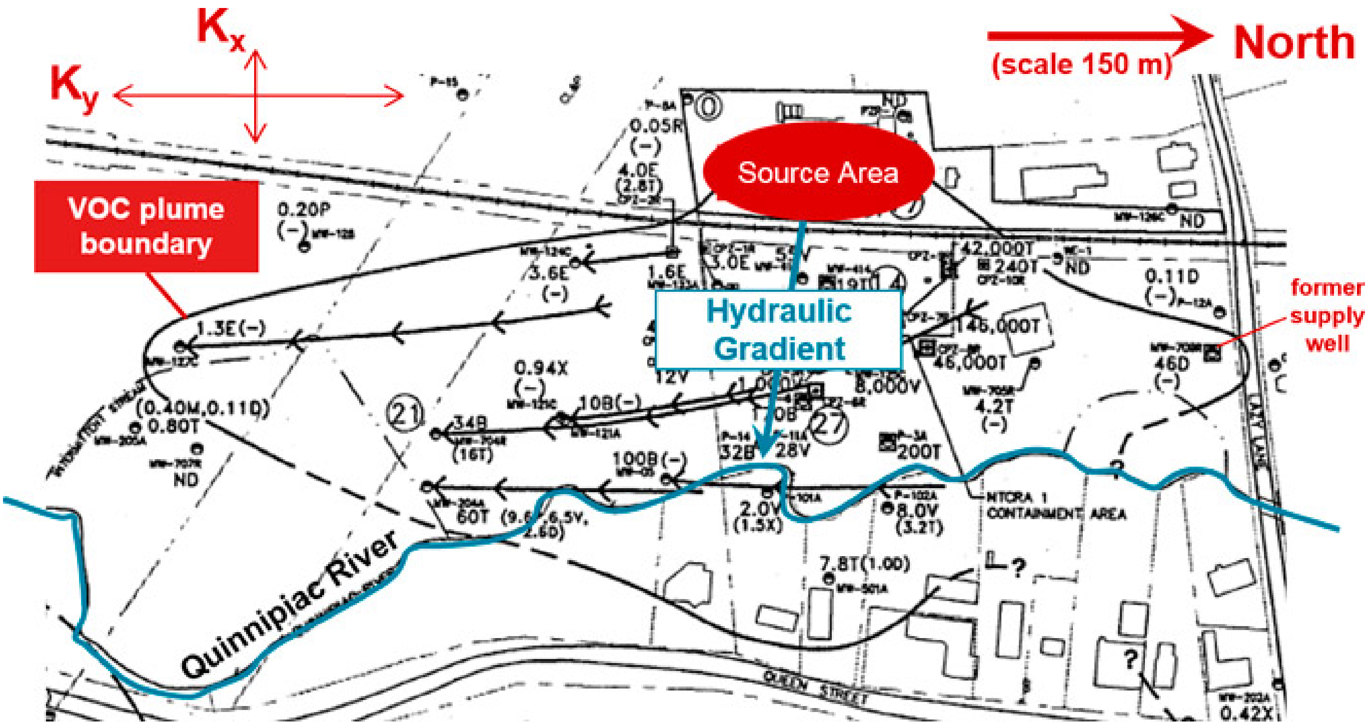

Figure 11-6. Particle tracking results using 1/20 plan-view anisotropy.

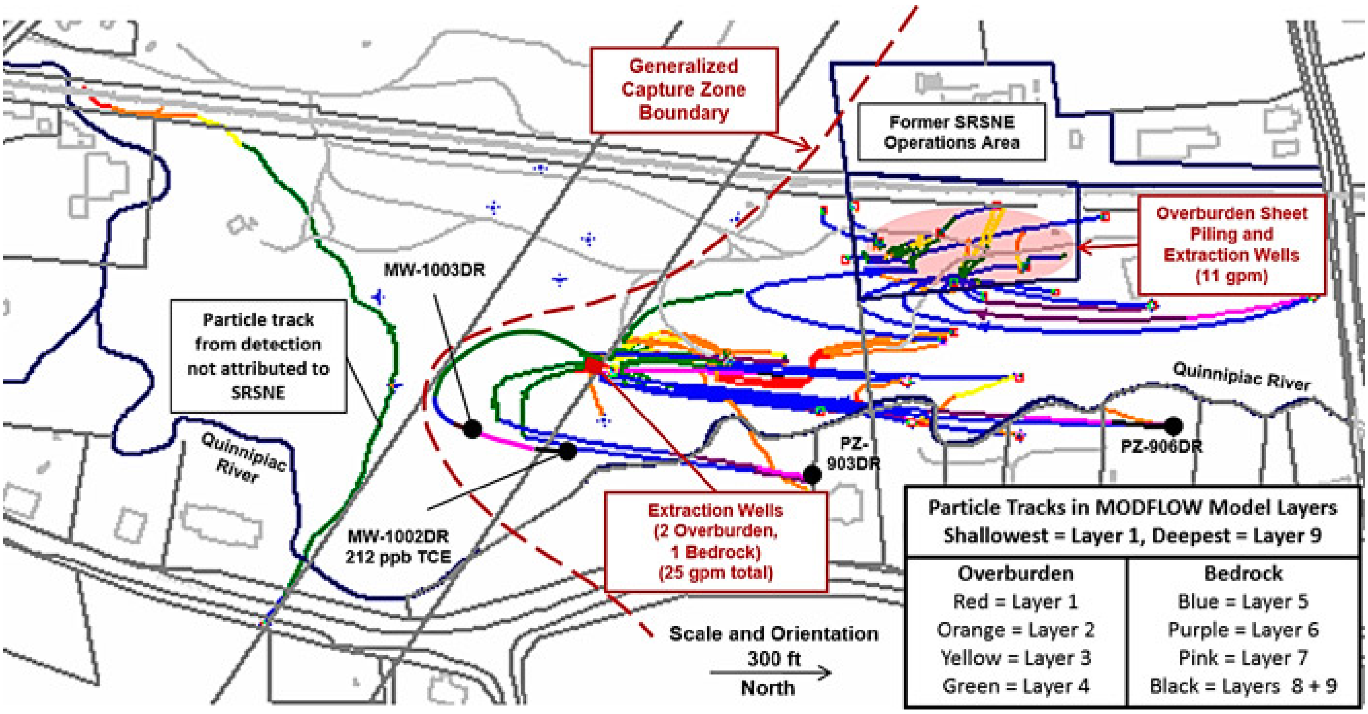

Figure 11-7. Hydraulic containment simulation with forward particle tracking from wells with VOCs above drinking water standards.

Plume Containment. Using the calibrated MODFLOW model with 1/20 plan view anisotropy, a bedrock hydraulic containment system was designed including overburden and bedrock extraction wells. Consistent with USEPA guidance, the capture zone was verified using multiple lines of evidence, including: modeling, hydraulic head mapping using numerous bedrock monitoring wells, and VOC concentration trend analysis at wells downgradient of the interpreted capture zone (USEPA 2008). Based on particle tracking simulations using a calibrated regional MODFLOW/MODPATH groundwater flow model, all monitoring wells where SRSNE-related VOCs have been detected above drinking water standards are within the capture zone established by the hydraulic containment and treatment system (Figure 11-7). The total pumping rate for all the extraction wells is typically 35 to 45 gallons per minute.

Bedrock DNAPL Zone Evaluation

During the RI, DNAPL was encountered in the overburden and the bedrock, and light NAPL liquid (LNAPL) was encountered in the overburden. NAPLs in each unit were delineated at two levels of relative confidence using multiple lines of evidence, consistent with research (Kueper 2009):

- Probable NAPL zone was delineated based on direct observations of NAPL, site history, anomalous VOC distributions or accepted technical principles based on effective solubility limits of NAPL constituents.
- Potential NAPL zone serves as safety factor around the probable NAPL zone, but also is consistent with effective solubility principles recognized as indicating the potential nearby presence of NAPL (USEPA 1992).

Comparisons to effective solubility accounted for the multicomponent DNAPL chemistry (Kueper 2009). The bedrock NAPL zone boundary delineated during the RI is shown on Figure 11-8. The potential bedrock NAPL zone was interpreted as extending generally east-southeast (down the dip of bedding plane fractures) from the former SRSNE Operations Area, but also northward (along strike) to the location of a former bedrock supply well that was used for truck washing.

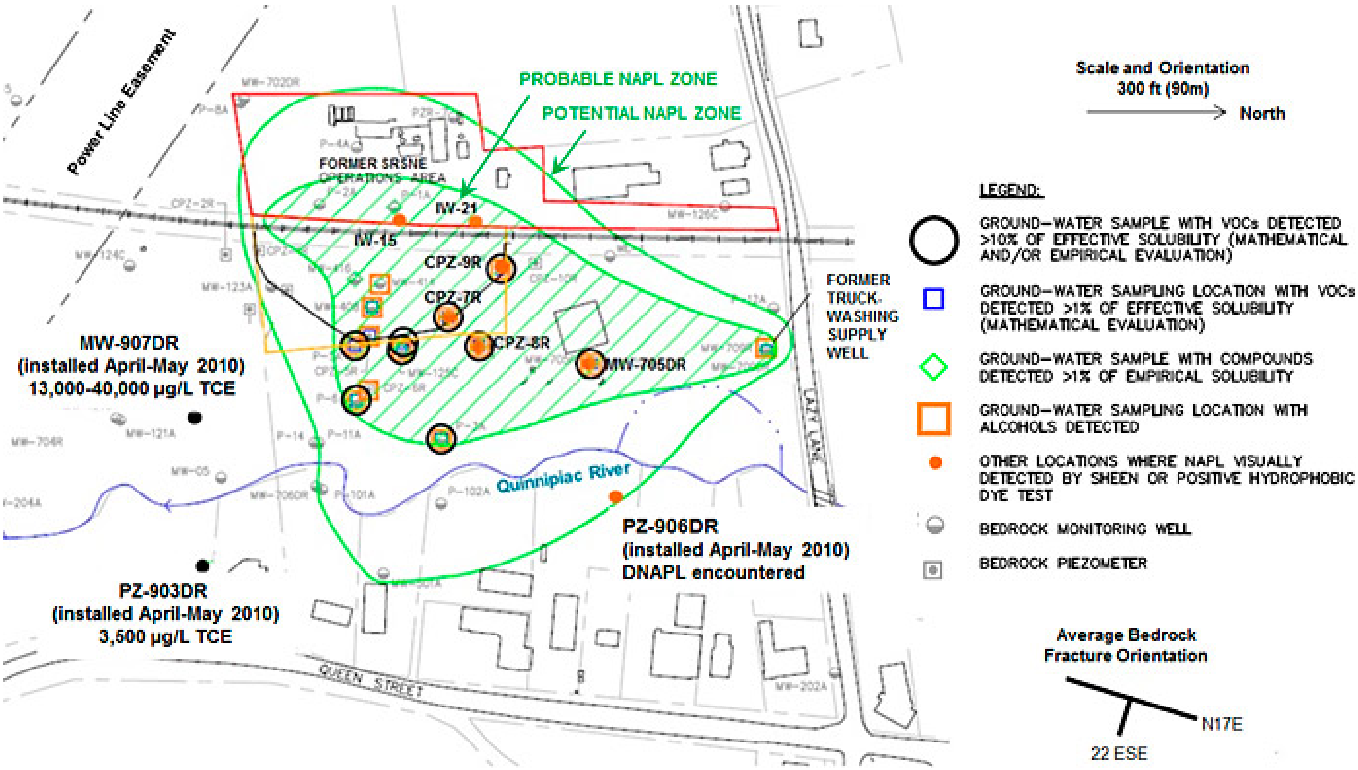

Figure 11-8. Probable and potential NAPL zone boundaries in bedrock delineated during 1998 RI.

Evaluation of Potential Downdip DNAPL Extent. During remedial design/remedial action (RD/RA) field investigations in 2009 and 2010, additional monitoring wells were installed to fill certain data gaps. One of the additional bedrock boreholes drilled at the eastern edge of the potential NAPL zone delineated during the RI (PZ-906DR; Figure 11-8) encountered DNAPL in fractures 170 to 177 ft bgs, 100 to 107 ft below the top of rock. PZ-906DR produced 13.4 gallons of DNAPL in six months, then stopped producing DNAPL. The DNAPL was chemically and physically similar to DNAPL samples previously collected at updip locations west of the Quinnipiac River, and consisted primarily of TCE with minor components of other organic compounds. This boring highlights the uncertainties in delineating NAPL in fractured rock, even a “Potential NAPL Zone” is used as a safety factor.

Figure 11-9 shows a 3-D Mining Visualization System (MVS) model looking toward the north-northeast along the average strike of the bedrock fractures and showing the shape of the interpreted bedrock DNAPL zone. Specific 3-D locations with visible DNAPL and/or sheens in bedrock are shown, and their locations align well with the average bedrock fracture orientation. DNAPL may extend even further downdip than PZ-906DR, and where DNAPL exists it dissolves and contributes to the plume of VOCs within the bedrock groundwater. Due to topography and drill-rig access limitations, direct delineation further down dip would likely require drilling many boreholes over 450 ft deep. Also, due to the complexity of DNAPL migration in fractured rock, delineation of mobile DNAPL by drilling cannot be considered definitive.

Estimate of VOC Mass in Bedrock

Dissolved and Sorbed VOC Mass. VOC attenuation has been observed within the bedrock groundwater, with an average bulk attenuation half-life of approximately 5.8 years in the shallow bedrock (top 30 feet of bedrock) and 17 years in the deep bedrock. These results are based on the temporal trend of total VOC concentrations in bedrock monitoring wells. Based on the mapped distribution of total VOC concentrations in the bedrock, the depth of the impacted bedrock and partitioning characteristics of the VOCs in the site-specific bedrock matrix, the total estimated VOC mass remaining in the dissolved and sorbed phases in the bedrock is approximately 12,000 kg.

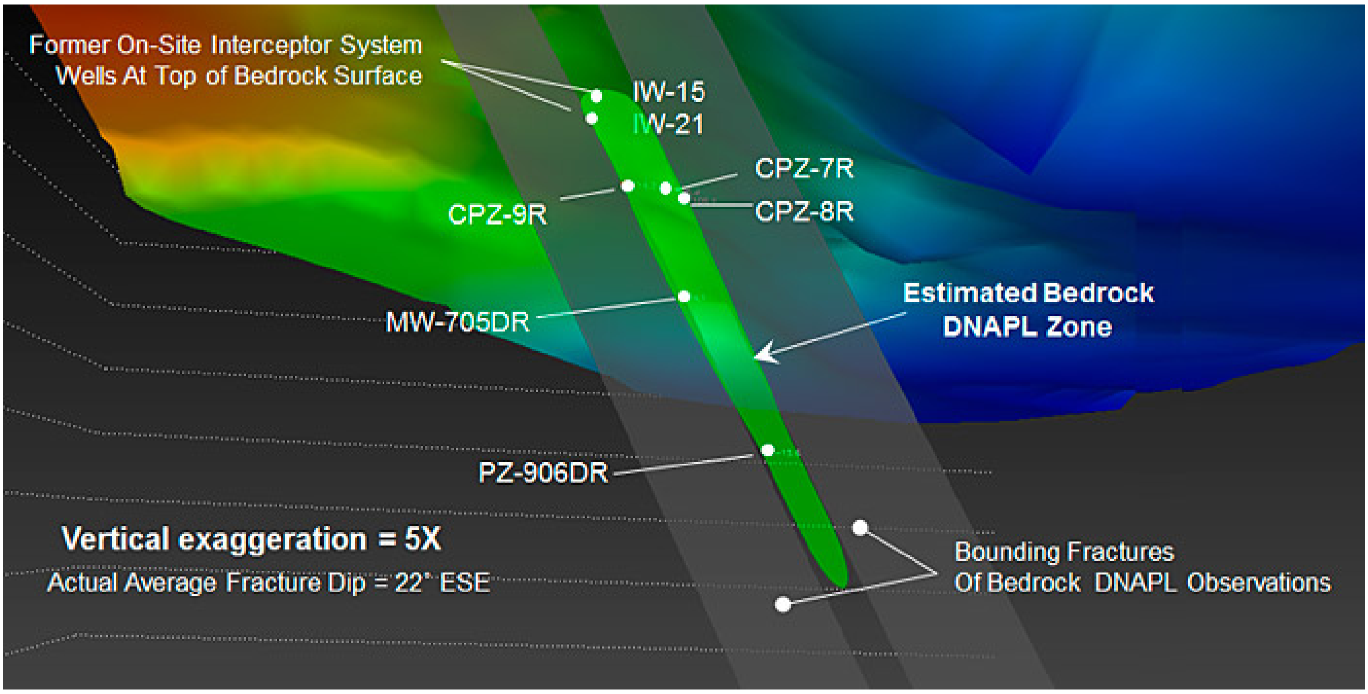

Figure 11-9. MVS model view toward east-northeast along average strike of rock fractures, with locations of NAPL or sheen in bedrock. Colorful surface at top is bedrock surface.

DNAPL Mass in Bedrock. As shown on Figure 11-9, the plan-view area of the revised probable DNAPL zone in bedrock is approximately 500,000 sq ft (11.5 acres). Based on MVS modeling and the locations where DNAPL has been observed in bedrock wells, the vertical extent of this zone is estimated as 60 ft, and oriented parallel to the average bedrock fracture dip. Thus, the total volume (Vtot) of the bedrock DNAPL zone is estimated as 30,000,000 cubic feet.

The DNAPL volume within the bedrock (V_{Db}) was estimated as:

$$V_{Db} = V_{tot} R_b$$

where:

V_{tot} = total volume of the bedrock DNAPL zone

R_b = DNAPL bulk retention capacity within the bedrock DNAPL zone

The bulk retention capacity, R_b, can be calculated as:

$$R_b = Q_{fx} R_{fx} F_{\%}$$

where:

Q_{fx} = fracture porosity (6.3×10^{-5})

R_{fx} = retention capacity of a single fracture contacted by DNAPL

$F_{\%}$ = estimated percentage of the fracture porosity that has been contacted by DNAPL

Laboratory research indicates that the retention capacity of a single bedrock fracture with an approximately 20° dip following DNAPL entry and drainage is approximately 7% to 17% (Longino and Kueper 1999). A single-fracture retention capacity value of 12% was assumed in these calculations. The term $F_{\%}$ accounts for the fact that, at the field scale, not all the fracture porosity within the probable DNAPL zone was invaded by DNAPL. Given the complex and variable nature of the bedrock fracture network geometry, aperture distribution, and fracture surface roughness, it is estimated that DNAPL may have contacted only 10% to 30% of the total fracture porosity within the probable DNAPL zone in the bedrock. Assuming the DNAPL contacted 20% of the fracture volume, the resulting bulk retention capacity is approximately 1.5×10^{-6} (1.5×10^{-4} %).

Based on the total volume of the revised probable DNAPL zone in bedrock and calculated bulk retention capacity, the DNAPL volume within the bedrock is estimated as 1,300 liters. Assuming an average DNAPL density of approximately 1.2 kilograms per liter (kg/L), this quantity equates to 1,500 kg.

Fracture Apertures Decrease with Depth

Figure 11-10 summarizes calculated bedrock fracture apertures versus depth below the top of rock. Each black data point represents a bedrock borehole interval where the mean hydraulic fracture aperture was calculated based on the measured interval K and average fracture spacing. The red dots indicate that the aperture of the specified intervals was below the indicated value, because the hydraulic conductivity value was below the lower measurement limit. The calculated fracture apertures generally decrease with depth. This finding is consistent with data reported by (Snow 1968) for sandstone and shale (gray data in Figure 11-10). With increasing depth, the weight of the overlying rock increases. The effective stress increases and causes the fracture walls to deform and flatten, decreasing the fracture apertures. Figure 11-10 also shows the fracture apertures that were assumed for TCE solute-transport modeling.

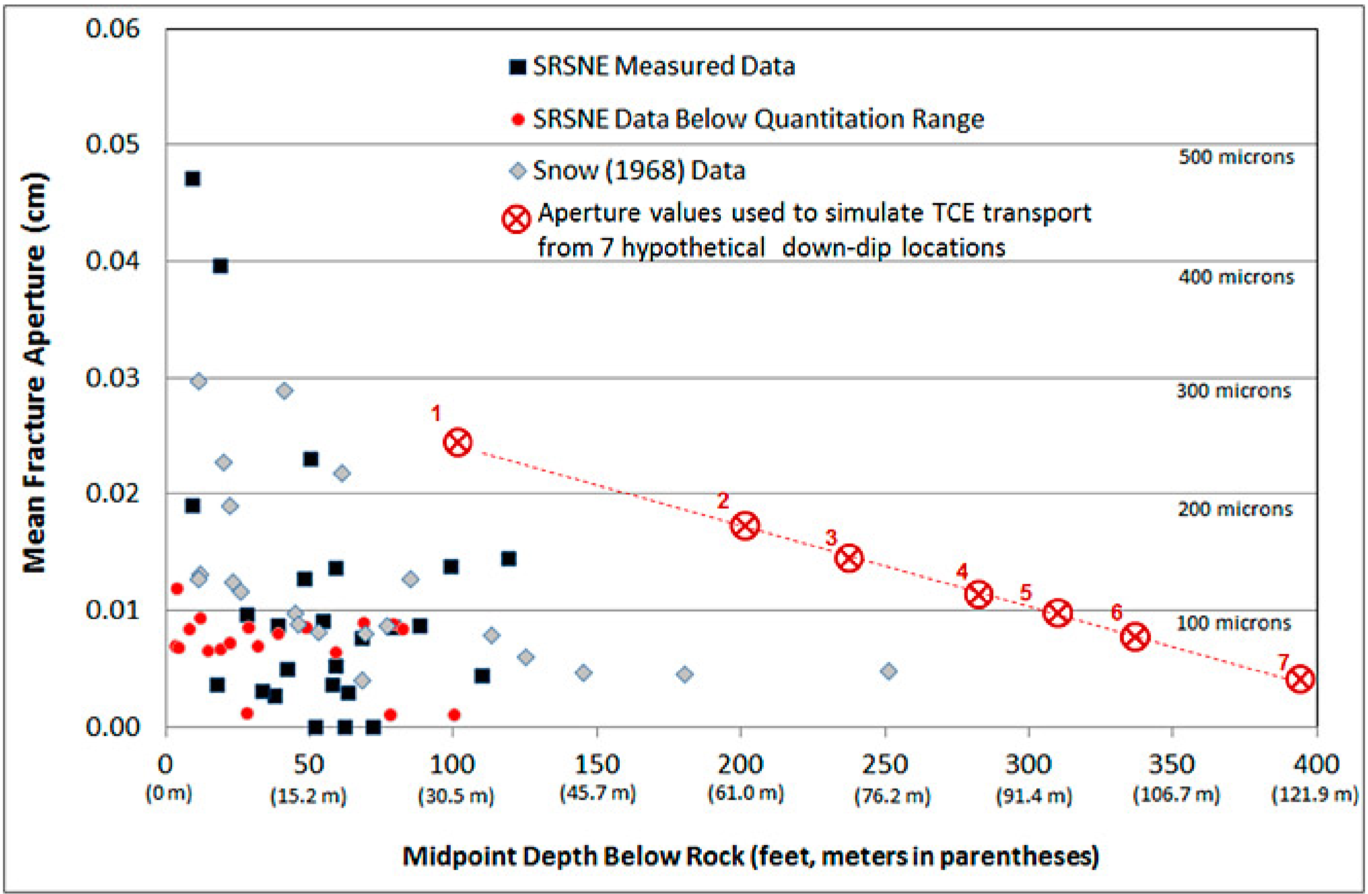

Figure 11-10. Mean fracture aperture versus depth below top of rock.

Solute Transport Modeling Approach

The Record of Decision for the site requires complete delineation and hydraulic containment of groundwater with VOCs above risk-based levels/MCLs. The downgradient extent of the bedrock NAPL zone and the eastern edge of the VOC plume in the deep bedrock east of the river were evaluated using a combination of particle tracking and discrete-fracture solute-transport modeling. TCE was selected for modeling because it has been detected at the highest concentrations relative to its drinking water standard in the area of interest, and it is the predominant constituent of the DNAPL. The dual-domain solute-transport analytical solution (CRAFLUSH), which was used to predict the dissolved plume length along select flow paths, is based on the work of Sudicky and Frind (Sudicky 1982).

The modeling approach assumes that DNAPL extends further down dip from PZ-906DR. A line of seven hypothetical down-dip plume starting points was considered, extending from a depth of 104 ft—consistent with the depth of DNAPL at PZ-906DR—to 392 ft below the top of rock (Figures 11-9, 11-10 and 11-11). Fracture apertures were assumed to decrease linearly with increasing depth. The estimated aperture at each depth was approximately two to four times larger than the largest measured or reported aperture value. The assumption of relatively large fracture apertures is believed to be conservative for the plume starting points, but also accounts for the expectation that as the plume migrates, it will flow upward within the bedrock and encounter increasing fracture sizes.

Other model input parameters include:

- bedrock matrix parameters based on site-specific measurements, as presented by Lipson et al. (2005)
- average fracture spacing (155 cm)
- measured hydraulic gradient component parallel to groundwater flow (0.005)
- constant TCE source concentration of 780,000 µg/L, as detected in groundwater above a DNAPL layer at bedrock well MW-705DR (Figure 11-12
- TCE degradation half-life (1,350 days)

The estimated half-life is based on mildly to moderately reducing conditions observed in bedrock groundwater east of the river (nitrate-reducing to iron-reducing) (Aronson 1997), but may be conservatively high (USEPA 2002b; Suarez 1999). The simulation time of 50 years was found to produce steady-state conditions (constant plume length and concentration profile in the direction of flow).

Modeling Results and Discussion

Two model “realizations” were developed, based on two bounding estimates regarding the potential southward extent of the DNAPL zone. For each realization, the conceptual boundaries of the bedrock NAPL zone were adjusted as shown on Figures 11-12 and 11-13. Realization # 1 evaluates the potential bedrock plume that would result if DNAPL extends further down dip from the location of PZ-906DR (Figure 11-12). Realization #2 evaluated the potential bedrock plume that would result if the DNAPL zone extends further south, directly down-dip from the former SRSNE Operations Area (Figure 11-12).

With increasing distance down dip, in the east south-east direction, the predicted steady-state plume length decreases due to decreasing fracture apertures and therefore decreasing groundwater velocity. The plume lengths shown on Figure 11-11 for starting point 1, and on Figure 11-12 for starting points 1 and 2, do not extend to the full calculated distance because those simulated particle tracks exit from the shallow bedrock (blue) to the deep overburden (green). Along the other particle tracks, the TCE plume is predicted to reach the MCL

before flowing upward to the top of rock. The estimated plume length downgradient from starting point 7 is approximately 30 ft. If DNAPL extends further down dip, beyond point 7, the fracture apertures would be expected to further decrease with depth and the resulting plume length would also be shorter than 30 ft, regardless of the down-dip DNAPL migration distance and depth.

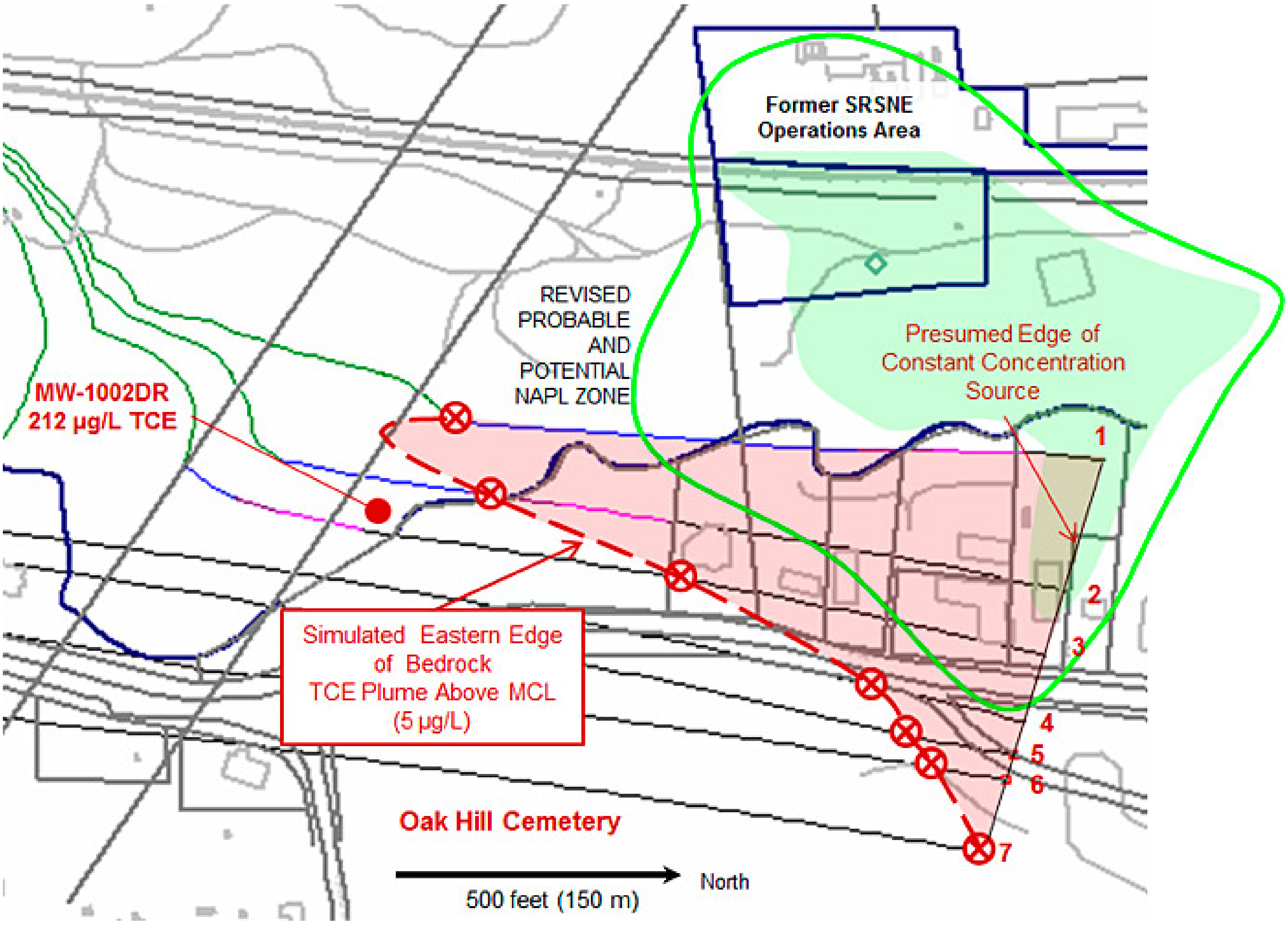

Figure 11-11. Realization #1 simulation results and "verification well. MW-1002DR.

Verification

Following the modeling work summarized above, a focused drilling and sampling program was performed to refine the bedrock DNAPL Zone and TCE plume boundary east of the river. Bedrock monitoring well MW-1002DR was drilled in February-March 2012 at a location between the eastern edges of the plumes predicted in Realizations #1 and #2 (Figures 11-12 and 11-13). Well MW-1002DR was installed with a screened interval of 171 to 186 ft bgs, where the highest TCE concentration was detected during vertical profiling (extraction packer tests samples). Sampling results from the new well indicated TCE at 212 µg/L. This detection disagrees with the results of Realization #1 (Figure 11-15), which predicted <5 µg/L at that location, but is reasonably consistent with Realization #2 (Figure 11-16). Based on the results presented above, the plume depicted in Realization #2 is believed to reasonably represent the steady state TCE plume in bedrock groundwater east of the

river. The potential NAPL zone in bedrock is interpreted to extend southward to the vicinity of point 3 shown on Figure 11-12, but the modeling results also account for the possibility that DNAPL could extend further down-dip to the east.

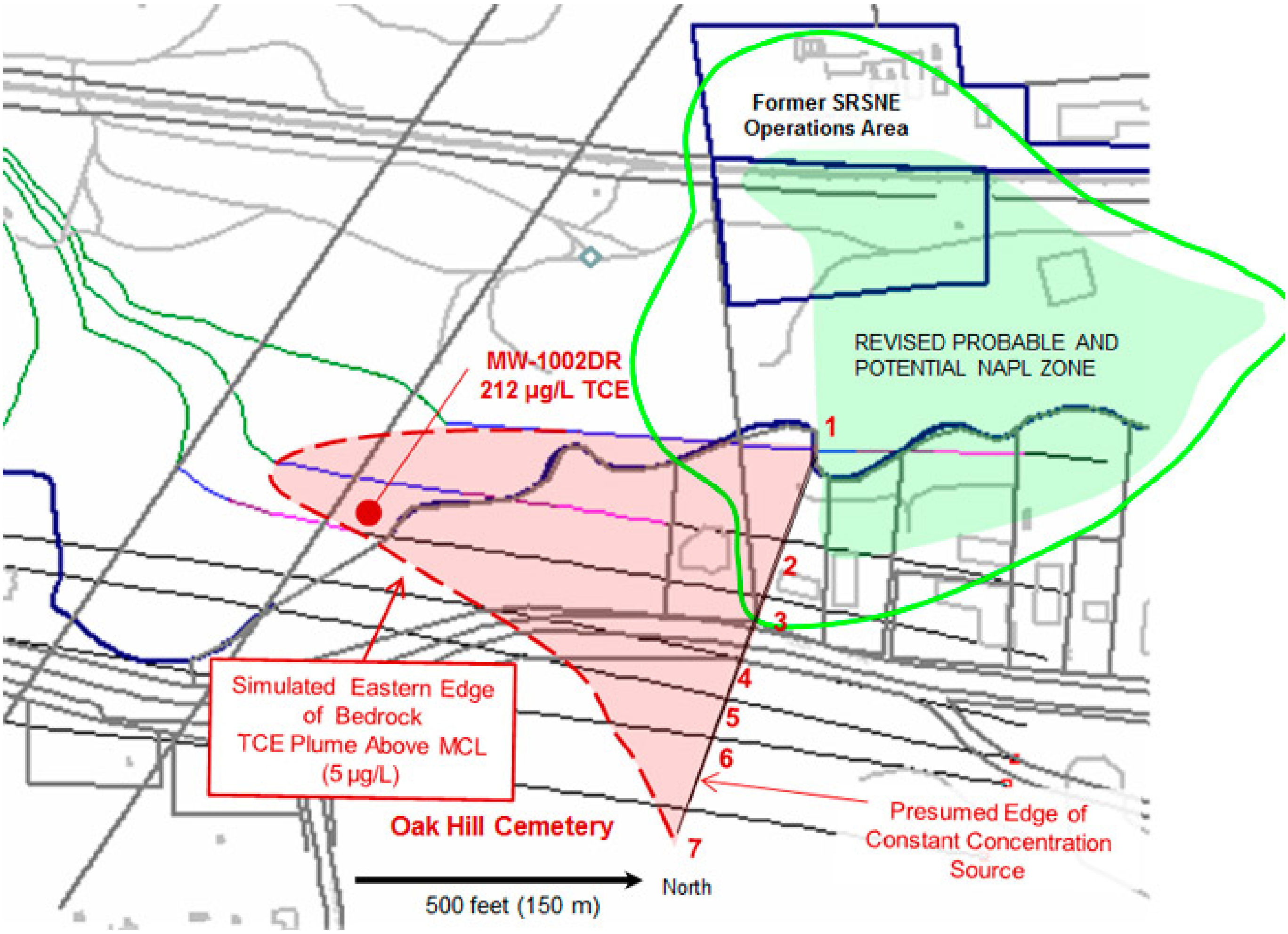

Figure 11-12. Realization #2 simulation results and "verification well. MW-1002DR.

Conclusion: No Completed Risk Pathway

Current and future risk and exposure are controlled, because: (1) VOCs do not exceed drinking water standards at wells beyond the capture zone of the hydraulic containment system, and (2) the plume is beneath a large cemetery and properties that will be subject to environmental land use restrictions. Also, an existing town ordinance prohibits drilling or use of potable water wells in the area. A focused drilling and sampling program has provided a basis to refine the bedrock TCE plume boundary location and, combined with modeling results, indicates that the potential for a completed risk pathway is extremely remote. USEPA indicated that this work completed the requirements for VOC plume delineation required in the ROD.

Lessons Learned

Through decades of work in the bedrock at the SRSNE Superfund Site, the following lessons have been learned:

- In this dipping, sedimentary bedrock setting, the orientations of the predominant fractures were inferred based on the mapped orientations of stratigraphic bedding but also confirmed via down-hole (in situ) fracture orientation measurements followed by stereonet analysis.
- Using groundwater flow modeling and particle tracking, the plan-view anisotropy can be calibrated within a bedrock formation to match the overall shape of a solute plume in bedrock.
- Calculating representative fracture hydraulic apertures is straightforward using bedrock intervals with known numbers of fractures and bulk interval hydraulic conductivity. At this site, the calculated hydraulic apertures decrease with increasing depth below the top of bedrock, consistent with expectations based on literature.
- DNAPL delineation is challenging, particularly in fractured bedrock. Even after using multiple lines of evidence and including a factor of safety (potential NAPL zone) drawn around the probable NAPL zone during the RI, DNAPL was encountered near the down-dip edge of the potential NAPL zone during the RD/RA. This result illustrates the importance of using a safety factor in DNAPL zone delineation.

- By measuring bedrock fracture orientations, apertures and spacing, and matrix parameters that affect solute-transport, solute-transport can be simulated in a manner that explicitly accounts for matrix diffusion and is useful for conceptual model development and risk evaluation.
- Using modeling and a well-developed, quantitative site conceptual model, it is possible in some cases to reduce drilling and complete the delineation of a deep bedrock VOC plume sufficiently to confirm the absence of a completed risk pathway.

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11.3 Characterization of Fractured Bedrock, United Kingdom

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HRSC Targets Impacts

High resolution site characterization (HRSC) enabled a targeted site investigation that delineated the depths of TCE impacts in near real time (optimizing drilling meterage) and demonstrated the presence of this solvent both within the fractures and diffused into the rock matrix. This information is critical to fully understand the CSM, improve remediation performance, and gain agreement of endpoints with the regulatory authorities in line with the client's objectives.

Site Description

The study site is an operational manufacturing facility, located in the United Kingdom (UK). A preliminary site investigation undertaken in April 2015 as part of a pending transaction identified impacts to groundwater from TCE, with concentrations detected at around 30% of the maximum solubility for TCE, suggesting the likely presence of DNAPL. In addition, TCE had been detected at downgradient third-party receptors. The study site had a long history of TCE use and several potential source locations were identified, including external bulk storage tanks, solvent transfer pipes and internal degreaser locations. Due to the high concentrations of TCE detected and the impacts upon third-party receptors, remediation was considered likely to be required.

Lithology/Bedrock Description

The study site is located on a hilltop, with thin soils over unweathered, fractured Upper Devonian shales/slates. These were folded and thrusted in the Carboniferous Variscan Orogeny, and a thrust plane was intersected at 58 m below ground level in the deepest monitoring well. Folds and thrusts verge to the north, whilst the main set of slatey cleavage strikes east, dipping at 60° S. Quartz-chlorite-calcite veins are present in tight, high angle sets, and in more massive, vuggy veins subparallel to the thrust and within fold cores.

Hydrogeology

Groundwater monitoring carried out between April 2015 and August 2015 indicated groundwater was present at between 12.2 and 15.6 m below ground level (m bgl). Groundwater levels showed high variability, with differences of up to 2.9 m in water level seen between monitoring rounds. Groundwater flow is complex within the fractured bedrock, but the overall bulk flow direction is to the east towards off-site receptors.

Contaminant Nature and Extent

The primary contaminant at the study site was TCE, with maximum concentrations in groundwater of 328 mg/l. TCE breakdown products, cis-1,2-dichlorethene and vinyl chloride were also detected at maximum concentrations of 3.7 mg/l and 0.07 mg/l, respectively. Traditional site investigation work in April 2015 identified impacts adjacent to the eastern boundary of the site based on a limited number of widely spaced boreholes; the nature of the bedrock had also not been fully assessed at this stage.

The study site had a long history of TCE use (45 years), however the potential date of any TCE release was not known.

Site Characterization

Site investigation activities in April 2015 had identified impacts to groundwater from TCE, which were likely to need future remediation. When designing the next phase of investigation there was no potential to investigate likely source areas inside the operational facility. The objective of the investigation was therefore to investigate accessible external locations to vertically and laterally delineate the contaminant plume and investigate pollutant linkages between the site and third-party receptors. The work was also to be completed within a short timeframe. Complex geological and hydrogeological conditions were anticipated due to the presence of fractured bedrock and the maximum depth of contaminant impacts was unknown. Based upon regional geological information impacts had the potential to extend to depths of over 100m bgl.

Site Characterization Approach/Tools

Traditional site investigation techniques were largely unsuitable for detailed site characterization, due to the fractured bedrock geology and likely complex contaminant distribution. With traditional techniques, rock samples would need to be sent to an off-site laboratory, with sample transport and laboratory turnaround times meaning results would not be available to inform the drilling depth and well installation for several days afterwards.

Therefore, to be able to rapidly collect data and install targeted groundwater monitoring wells a complimentary suite of high resolution site characterization (HRSC) techniques were chosen:

- CORE Discrete Fracture Network Approach (Core DFN), as developed by Beth Parker (2007) and provided by Cascade Technical Services, coupled with an on-site laboratory for VOC analysis of rock samples
- detailed structural and geological logging of cores (structural frequency analysis)
- down-hole geophysics (acoustic televiewer with automated structure identification and orientation)
- background fluorescence analysis (BFA)

These techniques were supplemented by traditional groundwater monitoring and then synthesized to develop a conceptual site model for the fractured bedrock. The drilling and on-site laboratory work were completed in two weeks and followed by traditional groundwater monitoring.

Results–Geology

The results of the acoustic televiewer, structural logging and frequency analysis and the Core DFN data allowed orientated structural features, such as fractures and bedding planes to be compared with TCE distribution to develop a fractured bedrock CSM. The fractured bedrock structural features are shown in Figure 11-13.

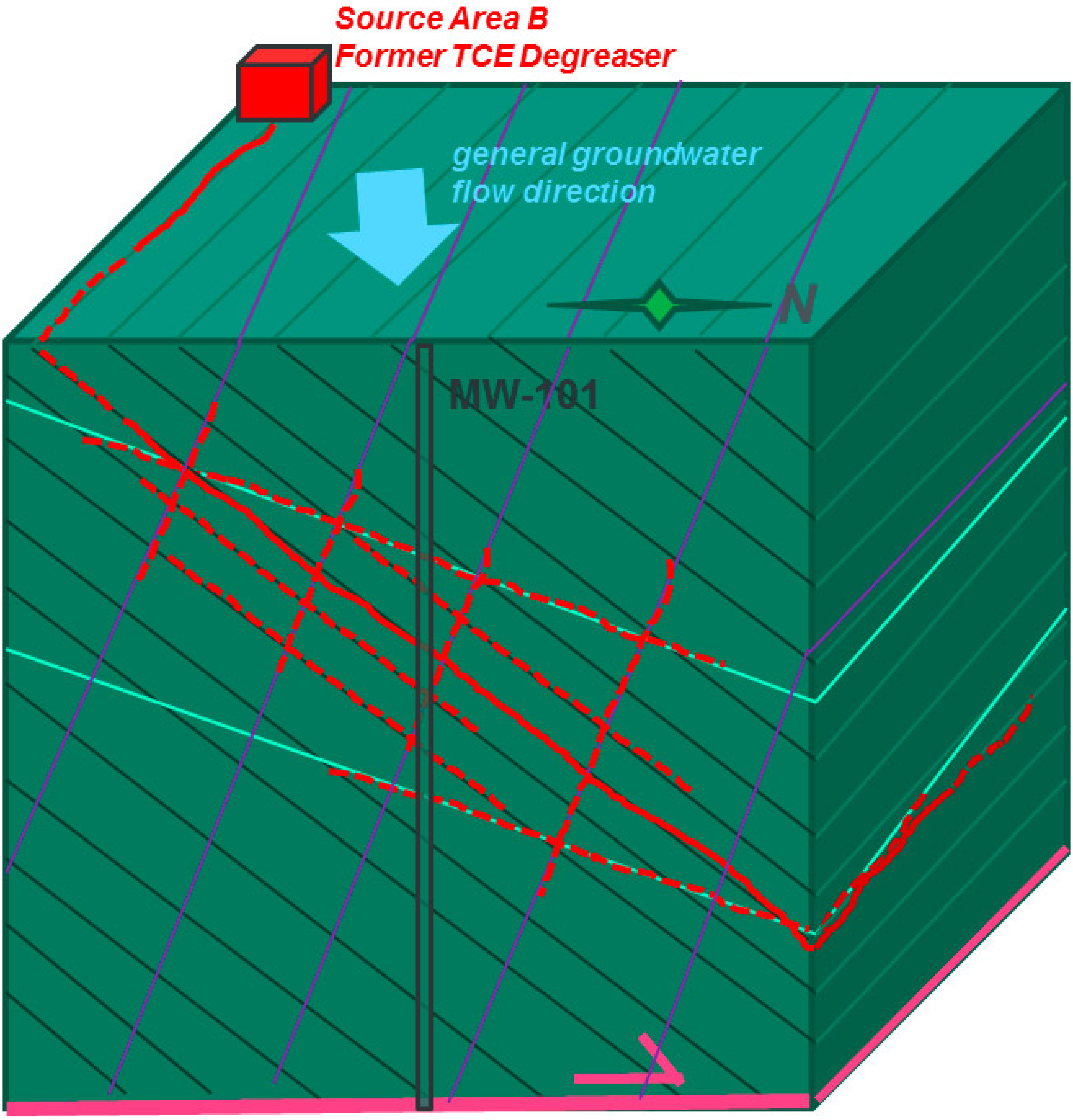


Figure 11-13. Fractured bedrock structural features for study site.

Note that the green parallel lines are bedding and bed parallel fractures (dipping 45°N), purple are slatey cleavage (dipping 60°S) and pale blue are a low angle open fracture set (dipping 30°N). The thrust is schematically illustrated as the pink line. TCE impacts in fractures are schematically indicated in red lines, solid to indicate >10% solubility, dashed to indicate lower concentrations in dissolved phase.

The fractured bedrock CSM highlighted the following;

- bed parallel fractures: frequent (1 or 3 per m), open (typically submillimeter aperture or microfractures) present almost throughout, but particularly on the upper limb of the fold-thrust structure between 16-36m bgl, where frequency was around 4 to 8 /m
- regional slate cleavage: common, high angle fractures (typically 0.2 to 1 /m), either tight or open (again, submillimeter aperture)
- low-angle open fractures**:** rarer (< 0.2 /m), typically open (around 1 mm aperture) and may be related to surface unloading
- veins: variable frequency, occurring in clusters of up to 8/m (steep, narrow vein sets were usually fully cemented

and tight, while the lower angle veins were vuggy with discontinuous apertures up to several millimeters)

In general, observable open fractures were rarer at depths greater than 40 m bgl, being generally restricted to veins, perhaps because of closure by lithostatic pressure.

From the Core DFN results, TCE has been found to have a variable relationship with structural frequency at different points away from the source area:

- The well closest to the source zone has highest concentrations (indicative of DNAPL), with significant concentrations in fractures down to 43 m bgl. Multiple TCE peaks correlate well with packages of high structural density in the shallowest 27 m, but not in the underlying 15 m.
- A well along strike and down the hydraulic gradient of the source area had TCE peaks that did not correlate well with high structural density.
- A distant well along the plume had very low concentrations of TCE and only in deeper stratigraphy (from 25-30 m bgl), with a single peak (still a relatively low concentration) correlating with high vein density.

The synthesis of the Core DFN data and the structural analysis indicates that TCE migration from potential sources is along both bed parallel and slate cleavage fractures. Both these structures strike approximately east-west, but dip in opposite directions, and are both cut by rarer low angle open fractures. This condition has produced a highly connected fracture network mesh, allowing a dissolved phase plume to travel down the hydraulic gradient.

Strata where there is a high correlation of structures-to-TCE represents areas where a single fracture set is transporting TCE (typically at higher concentrations, closer to the source area). Strata with poor correlation of structures-to-TCE are interpreted to be areas where multiple fractures in different orientations are transporting TCE (at lower concentrations, away from the source zone).

Results–Hydrogeology

The BFA identified potential hydraulic connections between monitoring wells located on the site and between the site and third party off-site receptors, as indicated in Figure 11-14. BFA uses the fluorescent properties of the organic content of groundwater samples to develop well-specific fingerprints, which are subsequently compared to predict potential hydraulic connections. The potential hydraulic connections identified support the likely TCE migration pathways identified within the fractured bedrock CSM and demonstrate the complexity of the subsurface.

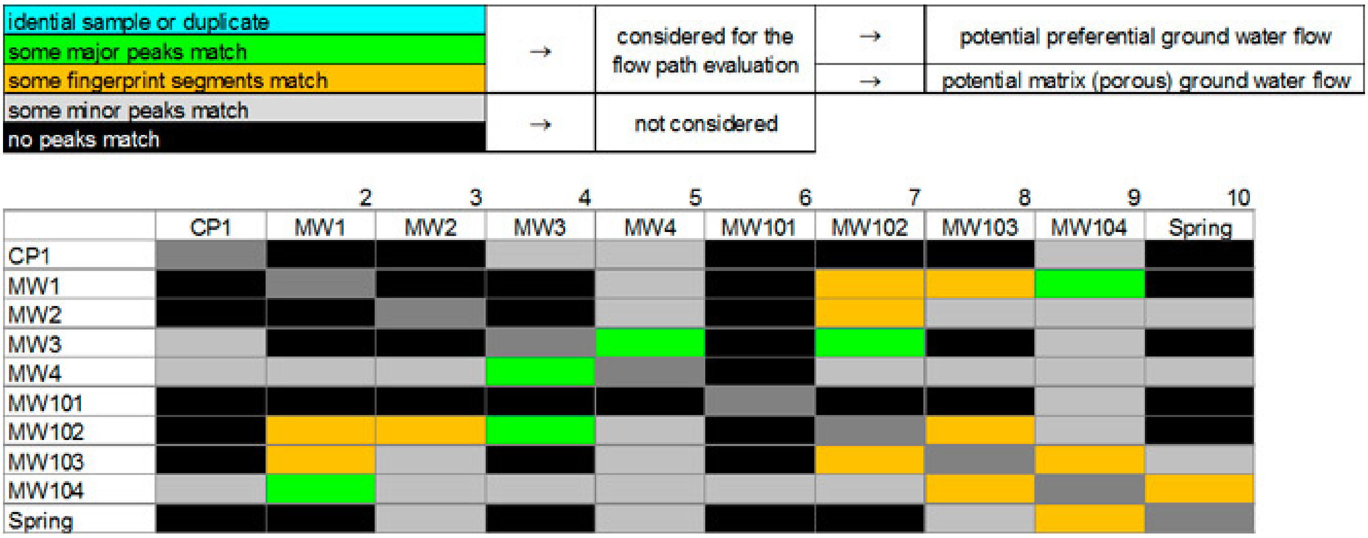


Figure 11-14. Background fluorescence analysis results.

Results–Source delineation

The use of Core DFN and analysis of rock samples using an on-site laboratory allowed the depths of TCE impact to be identified in near real-time. Rapid access to laboratory results informed decision making about drilling depth. Borehole drilling was then terminated once into 'clean' strata, reducing the operational drilling time spent on site. The first borehole drilled was advanced approximately 25 m into clean strata to confidently prove the maximum depth of impacts and this information was used to facilitate the earlier termination of subsequent monitoring wells, which were terminated less than

10 m into clean strata. In all cases, the base of the drilled boreholes was installed with a competent bentonite seal to prevent further downward contaminant migration and targeted monitoring wells were installed within contaminant transport zones (coincident with fractures). Figure 11-15 shows the vertical contaminant profile detected within the first borehole drilled, alongside the targeted monitoring well that was installed. In the case of this borehole, the decision was made to install a monitoring well targeting the high TCE concentrations detected at 37 m bgl, which corresponded with the location of a major fracture identified by the Core DFN and acoustic televiewer. The fractures with high concentrations located between 20-25 m bgl had also been targeted by an adjacent monitoring well installed during the preliminary site investigation in April 2015.

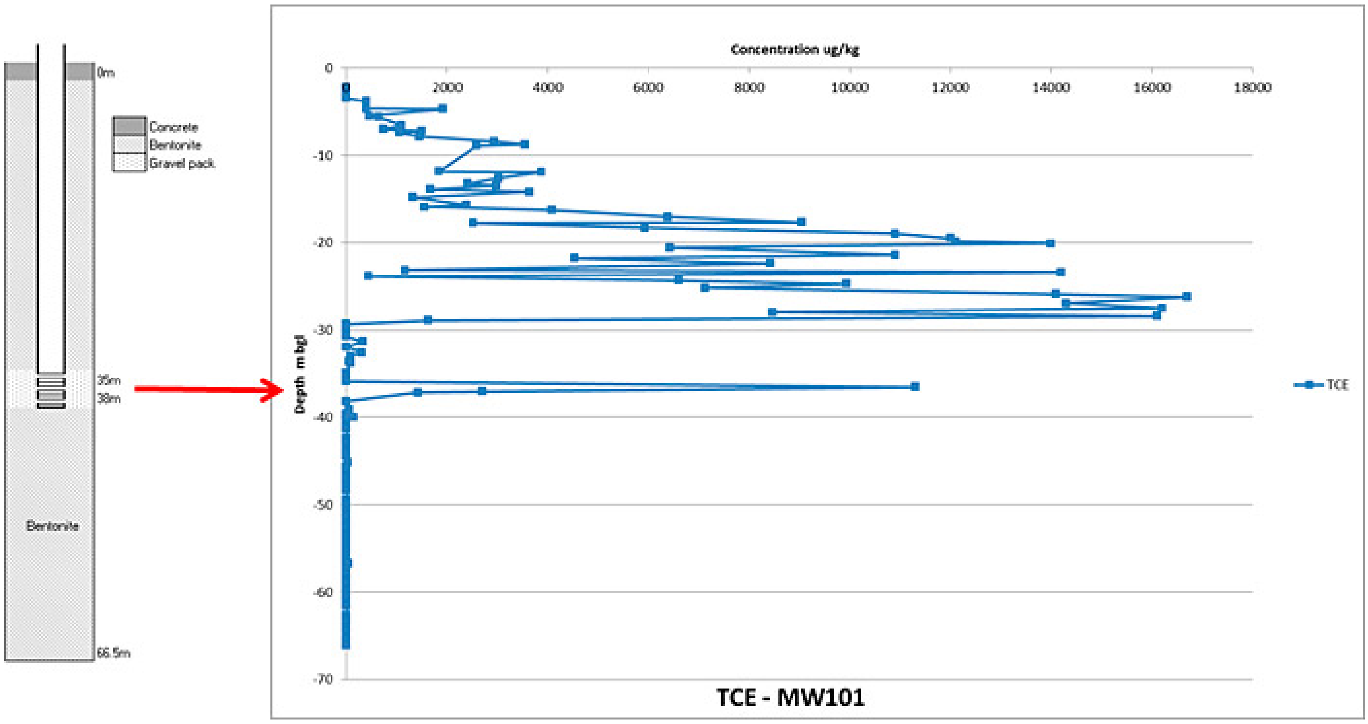


Figure 11-15. Vertical contaminant profile and targeted monitoring well installation.

During the HRSC investigation, a total of 351 Core DFN rock samples were collected from a total of 186.8 m of linear rock cores, across four borehole locations. All samples were analyzed on site for VOCs. To further assist in interpretation, samples were also analyzed for physical properties (porosity, % moisture, bulk density) allowing the calculation of porewater concentrations. Comparison of porewater concentrations with groundwater concentrations indicates that elevated concentrations of TCE are present within the groundwater and fracture network and are also present within the rock matrix.

Of the 351 samples collected, the majority were collected from fracture surfaces and located either immediately above or below a fracture. Furthermore, 73 samples were collected within the rock matrix away from fractures and of these, 30 contained concentrations of TCE above the laboratory limit of detection (LOD). Assessment of the 30 matrix samples with detections above LOD against the distance of these samples from the fracture surfaces suggests that TCE impacts have diffused a maximum of 365 mm into the slate bedrock matrix. This information suggests that TCE contained within the rock matrix represents a potential secondary source of contamination. The implications of the secondary source is considered as part of the remedial options appraisal for the site. Concentrations of TCE as determined via Core DFN and sample distance from a fracture surface are plotted in Figure 11-16.

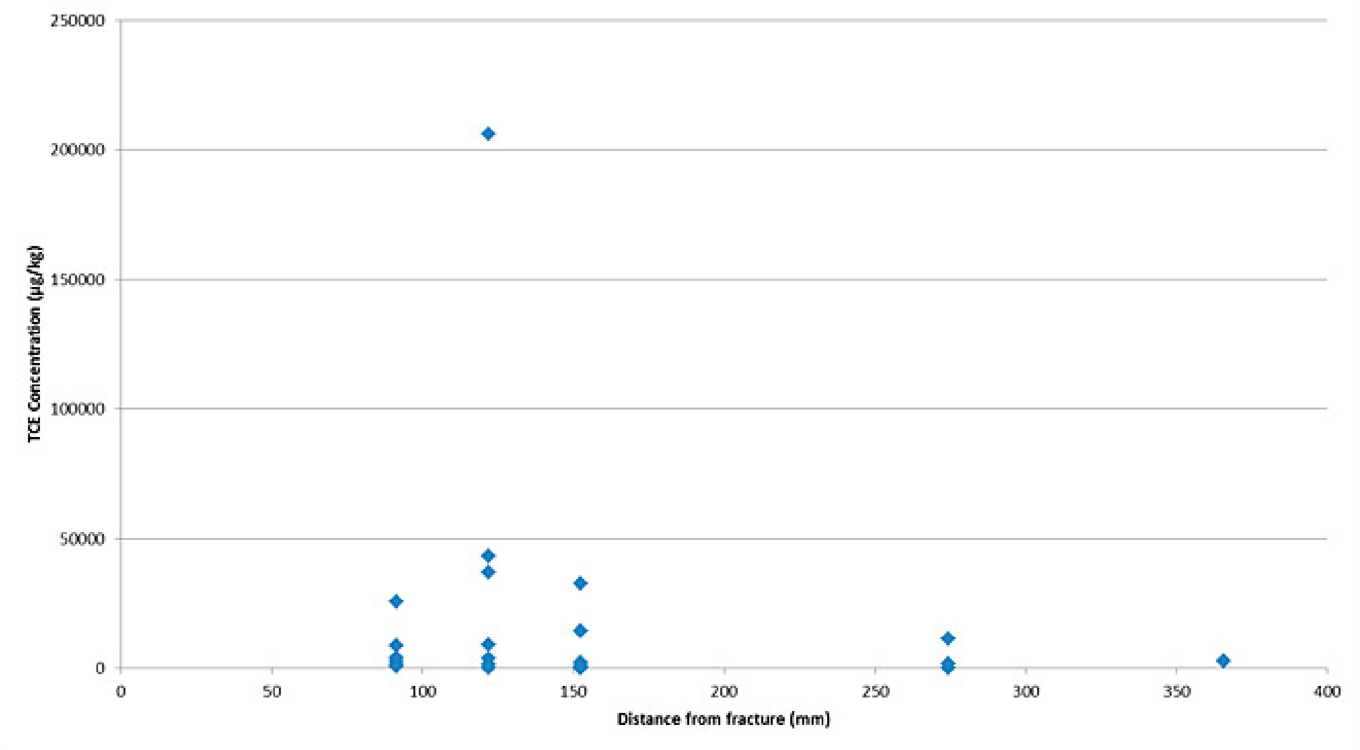


Figure 11-16. Plot showing TCE concentration in rock (µg/kg) vs distance of sample from fracture surface.

Outcomes and Challenges

The HRSC works used a complimentary set of techniques, bringing together multiple lines of evidence to produce a robust CSM. The HRSC techniques used also produced a high-quality data set within a brief time (drilling and laboratory mobilization of two weeks). The results of the characterization indicate the presence of TCE, both in the fractures and rock matrix, has informed the depth of impacts and provided information regarding the mechanisms for contaminant migration.

Data collected during the site characterization will be used to prepare a remedial options appraisal for the study site. Future remediation is likely to be challenging due to complex geology, depths of impact and presence of DNAPL. Pilot trials will be undertaken following the completion of the remedial options appraisal.

The collection of a large, robust data set has been used as the basis for technical discussions with local regulatory authorities, by demonstrating the complexity of the subsurface and has assisted in suggesting appropriate remedial end points in line with the UK risk based remedial framework. Positive feedback was received from the UK regulator regarding the works. HRSC assessment is to an extent an emerging technique in the UK and Europe and positive comments were received regarding the detailed approach to the investigation.

Lessons Learned

In the fractured bedrock setting, orientated information from downhole geophysics (optical or acoustic televiewers) allows full structural analysis beyond frequency plots and supports observations of fracture aperture. This is high-quality data that substantially improves the depth and breadth of the CSM and would also provide critical field data for any further numerical discrete feature network models.

The in-field Core DFN approach also allows site specific data to be gathered on the amount and nature of diffused contaminant vs contaminants in fracture groundwater. This is critical for the development of mass models, remedial options study and prognosis of long term rebound from back-diffusion. Remedial work undertaken on a site of the type described in this case study without the understanding gained from the Core DFN and structural data would have an extremely uncertain outcome, with a high risk of failure in the long term.

Appendix A. Karst Terranes

Karst terranes are distinct landscapes that develop when fractured, soluble bedrock interacts with surface water or groundwater to develop macroscale secondary porosity in the form of subsurface voids, conduits, and caves. Often, the presence of subsurface voids is expressed as distinctive surface landforms that are collectively defined as a karst terrane. However, dissolution and void development in soluble bedrock can also occur in the deep subsurface so that there is no land surface expression of the karst groundwater hydraulics.

Approximately 25% of the United States has the potential for karst development (Weary 2014), and it is estimated that as much as 40% of the U.S. population gets drinking water from karst aquifers.

Karst aquifers are, fundamentally, fractured rock environments. Soluble rock alone is not sufficient to generate a karst terrane, because these rock types often have low primary porosity that inhibits water infiltration and movement. For karst to develop, the introduction of groundwater through secondary porosity features, specifically fractures or bedding, is necessary. Groundwater flow in fractures or bedding of soluble rock is the embryonic stage of karst development, often generating anastomosing dissolution features. As groundwater moving through the fractures continues to dissolve the host rock, the solution features enlarge and the fracture system becomes increasingly more karstic.

Most karst landform development occurs in highly soluble carbonate and evaporite bedrock, such as limestone, dolomite, marble, and gypsum. However, all bedrock is soluble to some degree, depending on the rock and groundwater chemistries. Solutionally enlarged fractures have been found in granular, nonsoluble rock (Halliday 2007), sinkholes have developed in sandstone (Alexander 2005), and karst-like groundwater flow has been reported in sandstone and quartzite (Wray 1997). Additionally, conduit flow and similar landforms can develop in vesicular basalts and in association with volcanic lava tubes. Often, these noncarbonate terranes are referred to as *pseudokarst*.

For site investigation and management of karst aquifers, these terranes are often viewed as mysterious areas where the standard principles of hydrogeology do not apply and where even data from the most basic tools (such as monitoring wells, potentiometric surface maps) are often unreliable or confusing. Like other fractured bedrock environments, groundwater investigations in karst often end up with numerous monitoring wells with a variety of different heads and chemistries depending on which fractures or conduits are intersected. However, with a working knowledge of karst aquifer characteristics and how its development and morphology can affect localized and regional groundwater flow, an effective investigation can be easier to design and implement that those in other fractured rocks—especially if approached at the macroscopic scale.

Because karst groundwater systems often develop a diverse landscape of macroscopic scale features like caves, sinkholes, sinking streams, and large springs, they are often more easily identifiable than other fractured rock environments. In the subsurface, the conduits and interconnected solutional features develop hydrologic systems that in many ways behave as surface drainage basins. Additionally, karst surface features can provide clues to the location of the hidden subsurface drainage patterns, streams, and resurgences (points of exposure). By understanding how these macroscopic features develop, it is often possible to begin to decipher the groundwater flow directions and patterns in the subsurface and develop a preliminary CSM without conducting any intrusive activities.

A.1. Identification of Karst Terranes

As with any environmental investigation, development of the typical CSM begins at the macroscopic scale. To understand the karst environment, the researcher should take a systematic approach to build the model through a process often referred to as a karst features inventory. A karst features inventory is simply an accounting of recognizable karst features, beginning at the macroscopic scale, and eventually using those features as indicators of both the surface morphology and the subsurface architecture (i.e. the fracture and conduit system) (Quinlan 1991).

Topographic and geologic maps along with aerial photography are often excellent resources for identifying the presence and degree of shallow (near land surface) karst development. Any closed depression identified by hachures on a topographic map should be identified as a potential solutional feature for further investigation. Areas that appear to lack surface drainage features also suggest a dominant subsurface drainage system. Blind valleys with streams that disappear or that appear from large springs are other easily identifiable indicators of karstic systems. Even place names on topographic maps such as Bottomless Lake, Big Sink, Cave Springs, Dry Valley, Lost Creek, or Sinking Creek can be good indicators of karst.

Geologic maps can be used to identify the extent of any soluble rock formations exposed at the surface, but be careful to evaluate potential karst formations that may be present beneath the surface rock as well. Many of the most extensive cave systems in the world (for example, Mammoth Cave in Kentucky) are developed beneath a caprock of sandstone.

Aerial photographs are helpful in some areas, for instance circular lakes in Central Florida, circular areas of lush vegetation in arid regions of Texas and New Mexico, or groupings of trees in otherwise cultivated land in the Midwest are all worthy of closer scrutiny. Additionally, recent advances include high resolution light detection and ranging (LiDAR) data to develop improved sinkhole maps in Kentucky (Zhu 2014).

Soils maps can also be used to aid in karst identification. Karst areas often have a conspicuous "terra rosa" coloration and the soil type may be different in a depression that is internally drained compared to the surrounding soils. Soils in karst areas commonly exists as a thin layer over the bedrock or may not be present at all.

The following descriptions summarize some of the common surface features that can be indicators of karst development.

A.2. Sinkholes and Dolines

Sinkholes are defined as closed topographic depressions, typically circular to subcircular and with side slopes ranging from shallow to vertical that form from dissolution, collapse, or subsidence of the underlying rock. The term *doline* (Cvijic 1893) takes precedence in international literature and is preferred in Europe, but in the U.S., *sinkhole* is the term used most often. Sinkholes form as the result of several processes related to dissolution, and they are considered an index landform for karst. They can range in size from a few feet to over 20 miles in diameter. They are usually dry, but if they intersect the water table or become sediment clogged, they can be filled with water. Sinkholes are important recharge features to a karst aquifer system. Note that only large sinkholes are found on topographic maps. One study found that 85% of the sinkholes in Winona County, MN, were not shown as depressions on the 7.5 minute topographic maps compared to field investigations (Dalgleish 1984).

Some karst-prone areas have developed databases documenting the locations and types of karst features, particularly sinkholes, to help with land management and planning. These databases, if available, can be a useful aid for CSM development.

A.3. Springs

Proper delineation of springs is an essential element in understanding the transport and discharge of groundwater in a karst hydraulic system. While large springs are not unique to karst, they are a common karst feature and some of the largest springs in the world occur in karst aquifers. Springs are an essential part of a karst characterization. Like other fractured rock aquifers, springs represent discharge points of the solutional channel network and therefore may include inputs from sources from a large catchment area.

Like sinkholes, only the largest springs can be identified from topographic maps and smaller springs and seeps may only be found through field reconnaissance. Springs may also discharge underwater (in lakes, streams, or coastal environments), making their detection more difficult. Often, they can only be found through careful delineation within a water body or indirectly through calculating a water budget. Determination of source areas and catchment basins for springs often involves the use of tracer studies (fluorescent dyes or other techniques) to determine flow pathways and source areas for individual springs.

Sinking Streams and Dry Valleys

The lack of surface streams in a humid environment is a common indicator of subsurface drainage. This may also be seen in valleys with upland streams that abruptly disappear when they reach the valley floor or a stream valley that abruptly ends with no apparent outlet. Larger sinking streams are often visible on topographic maps and aerial photographs. In humid regions, the streams may be obvious, but in arid regions, such features may be blind arroyos or small canyons devoid of visible streams. These macroscopic features can most often be found through a review of maps and aerial photographs.

More difficult to observe are streams that are losing or gaining in less dramatic fashion, but also may be indicators of karst development. Any area underlain by soluble rock and generally lacking surface drainage features should be suspected of subsurface drainage.

A.4. Epikarst and Karren

Epikarst, related to *karren*, is a term used to describe the complex uppermost, near-surface portion of a karst system that includes the soil/bedrock interface. The epikarst is generally defined as the irregular, solutionally-derived bedrock surface that is often hidden beneath a layer of soil. The epikarst often includes perched groundwater conditions that are more susceptible to surface contamination (Cooley 2005). The epikarst is also a primary recharge pathway that funnels infiltration from the soil and surface features into the underlying conduit system. Generally, epikarst is comparable with the vadose zone, but may also include permanent or seasonal phreatic conditions depending on water table depths and aquifer morphology. The epikarst is one of the few portions of the karstic system that may provide aquifer storage (Williams 1983).

Karren is a broad term that refers to solutional fissures, rills and grooves often seen on rocks at the surface as part of the epikarst. These features may be spread over large areas and even seen on a microscopic scale. Often, these features are the result of solutional enlargement of bedrock fractures and can be important indicators for bedrock structures and local or regional fracture orientation. Karren can form a pavement when devoid of soil and may form a rectilinear *clint and grike* landscape (Ford 2007). In the U.S., karren is often soil-covered and is manifested as *pinnacle and cutter* structures at the soil/bedrock interface.

A.5. Caves

In simple terms, a cave is defined as a natural underground opening that is large enough for human entry (Ford 2007). This definition could include large vugs or voids, but such features are uncommon.

Cave are considered fragile habitats, and many caves have resident endemic, threatened, or endangered species. Consequently, the presence of caves near a contaminated site requires a greater degree of investigation to include potential faunal impacts that is beyond the scope of most site investigations. If a cave is near a site, consult with the National Speleological Society or state and local cave organizations, which potentially have locations, maps, and other data for area caves.

Animals may frequent openings that do not meet the definition of a cave, but may lead to larger openings or a cave accessible from a different location. In addition, cave-sized openings may be encountered at depth while drilling and may be identified on drillers' logs as voids or rod drops. A cave can open underground and still be inhabited. For example, two species of threatened blind catfish from the Edwards Aquifer near San Antonio, TX, are known only from individuals that have been recovered from water pumped to the surface from wells that are 1,350 to 2,000 feet deep.

The presence of large (or long) cave systems also can have a significant effect on local and regional water quality. Large cave conduits can transport large quantities of water over long distances in short time periods with little or no degradation of introduced contaminants.

A.6. Karst Site Characterization Methods

Karst sites and more traditional fractured rock sites have much in common. Consequently, the investigative techniques are often similar. Careful logging of borings and bedrock core, coupled with packer testing, surface and downhole geophysics, and many of the other common fractured rock investigative tools are also useful in karst environments. Some specific characterization methods and tools, however, have been developed to address the specific challenges of characterizing karst aquifers including those briefly outlined below.

A.7. Karst Features Inventory

A karst features inventory is a combination of desktop and field observations. The first step in site characterization and development of a CSM is to review available maps, photographs, and literature to locate and document identifiable karst features such as sinkholes and springs that may provide information with respect to subsurface flow conditions and preferential pathways. Because karst drainage basins can be large, desktop reviews should include the subject property, as well as surrounding properties and the region. Often, a primary groundwater resurgent spring is located several miles from a source area.

Many karst features are not discernable based on desktop surveys alone because they are too small or may be obscured by vegetation or topography, so field reconnaissance by a qualified geoscientist becomes valuable. Depending on the size of the study site, field inventory surveys involve a walking survey of accessible areas to identify and document karst features and to verify those features tentative identified from maps and aerial photographs. Typically, a survey uses an inventory form to quickly determine the feature identified. This form may include general information such as the features type, location (GPS), size, and other relevant information. If the feature is a spring or other groundwater resurgence, the estimated discharge should be recorded along with the temperature, pH, and specific conductance of the water if the appropriate instrumentation is available.

A good reference for conducting karst inventories/site assessments is the Texas Commission on Environmental Quality (TCEQ) *Instructions to Geologists for Geologic Assessments on the Edwards Aquifer Recharge/Transition Zones* (TCEQ 2004).

Some state agencies (such as Kentucky) allow the use of karst springs as groundwater monitoring locations in place of monitoring wells if they can be shown to be representative of the groundwater source area in question. Consequently, locating and characterizing these features becomes an important part of establishing a CSM for subsequent aquifer characterization, monitoring, or remediation.

A.1.1 Tracer Testing

Fluorescent dye tracer has long been used to determine groundwater flow paths in fractured rock environments, especially karst terranes. By injecting one or multiple nontoxic fluorescent dyes, it is possible to trace the dye’s movement through individual fractures and groundwater flow paths either visually or analytically (with the use of spectrofluorimetry). Dye tracing can provide valuable information about groundwater flow direction, preferential pathways, travel times, storage, or residence times. Dye tracing also provides insight into potential solute advection, dispersion, and dilution depending on the test design and equipment used. Proper test planning and execution by experienced personnel is essential to prevent cross-contamination and false positives, because many of these dyes can be detected at the ppt level.

Tracer tests can be conducted using a wide range of injection and monitoring points varying from naturally occurring springs to monitoring wells. Trace lengths can vary from tens of feet to tens of miles depending on site conditions and project needs. Some understanding of the site geology, fracture orientation, and groundwater flow is valuable to allow proper dye receptor placement and sampling frequency. In poorly understood or complex systems, it may be necessary to deploy many receptors to account for all probable flow scenarios to maximize the likelihood of dye recovery.

Dye tracing can be conducted by two different methodologies: qualitative and quantitative (USEPA 1988). Qualitative tests involve sample collection using passive dye receptors, typically small mesh screen packets filled with activated charcoal. Qualitative tests are used primarily for determination or confirmation of groundwater flow direction/pathway and delineation of drainage basins.

Quantitative tests typically involve the collection of discrete water samples for analysis and use automatic samplers to collect frequent samples over extended time intervals. Quantitative tests can also be conducted using field spectrofluorimetry instruments for real time data collection. Quantitative tests are used primarily to determine groundwater travel times and higher-level flow dynamics such as advection, dispersion, dilution, and residence time. A tracer analytical computer program, QTRACER2, can analyze tracer breakthrough curves to derive aquifer characteristics (USEPA 2002b).

While fluorescent dyes are the most common tracers used, successful tracer tests have bee conducted using a variety of other materials depending on the site conditions, tracer objective, and available material. Some examples of alternative tracers include:

- salts such as sodium chloride potassium chloride, and lithium chloride
- bacteria or other distinctly identifiable (nonpathogenic) microorganisms
- stable and radioactive isotopes
- buoyant artificial materials such as plastic spheres and shredded paper

A.1.2 Drainage Basin Analysis

Delineation of drainage basins in karst aquifers is an important tool in understanding subsurface flow dynamics and pathways. Because of the dominant fracture and conduit controlled pathways, it is not unusual for separate recharge features that are near each other to have completely different flow directions and transport times. Additionally, evaluating the inputs (such as precipitation or surface streams) and outputs (springs, seeps, and water withdrawal wells) can help characterize the storage and movement of water through the basins.

A good case study is the basin delineation study performed at the Fort Knox Military Reservation in north-central Kentucky to develop appropriate groundwater management and monitoring strategies. The study resulted in the delineation of more than 28 individual drainage basins covering over 130 km^2 containing over 200 inventoried karst features. The basins were delineated using a combination of dye tracing, structural and topographic controls, spring characterization, and normalized base flow (Connair 2002).

When working within multiple drainage basins, normalized base flow (NBF) can be an effective tool to evaluate the size and hydraulic character of individual basins. Designed to evaluate surface drainages, NBF can also be applied to karst drainage basins (Quinlan 1996). The method assumes that basins in a similar physical setting and climate have a similar base flow discharge per unit drainage area (in cubic feet/second/square mile of basin area, or cfsm). Comparison of NBF values for individual basins against a regional (or average) NBF value can identify basins that have anomalous discharge values. Anomalous values are indicators of additional, unrecognized natural or artificial inputs, improperly delineated basin boundaries, or unidentified flow paths and discharge points.

A.1.3 Spring Hydrographs

> *"The spring is the pulse of a karst aquifer."*
>
> *(Quinlan 1991)*

Plotting spring hydrographs of discharge through time, especially in conjunction with precipitation, can provide important insight into the characteristics of the aquifer. Typically, karst springs tend to have a rapid, "flashy" response to precipitation events because the low primary porosity of the host rock and resulting limited groundwater storage potential. Bonacci (Bonacci 1993) showed that by analyzing the regression curves of spring hydrographs, it was possible quantify some of the aquifer storage and transportation characteristics. When a spring hydrograph is at its peak following a precipitation event, the karst aquifer storage is at its maximum and the slope of the subsequent regression curve is an indicator of the rate of withdrawal (Ford 2007). Additionally, evaluation of the different subsegment slopes in the hydrograph regression curves can be used to calculate specific yields associated with three types of karst aquifer storage: conduit, fracture, and matrix (Shevenell 1996).

A.1.4 Analytical Models

The application of analytical or digital models for karst aquifers is much more challenging and complex than nonkarst or homogeneous and porous aquifers. An inclusive karst aquifer needs to account for the effective triple porosity of the system including the pore matrix, fractures, and conduits or solutional voids (Palmer 1999).

However, most analytical modeling efforts typically focus on one, or at most two, porosity pathways. Additionally, most numerical groundwater models are based on laminar flow (Darcy's Law); however, groundwater movement through the karst aquifer is often subject to turbulent flow through larger aperture fractures and conduits (Ford 2007).

Palmer (Palmer 1999) notes:

> The heterogeneity of kart aquifers is so severe that it is virtually impossible to acquire sufficient field information to construct a predictive digital model trustworthy enough to allow extrapolation of heads and flow conditions from known to unknown locations, let alone into the future.

With the understanding of these limitations, analytical models can provide predictive information about potential water flow, chemistry, and fracture/conduit development and orientations. Furthermore, with continued improvement in analytical model development and computing capabilities, model quality and complexity continues to improve.

A.8. Groundwater Flow in Karst Aquifers

General fracture flow mechanisms and the principles of groundwater movement through fractured bedrock aquifers also apply to karst. Karst aquifers, however, also have distinguishing hydrologic characteristics that are specific to soluble rock environments. Entire books are devoted to the topic of karst hydrogeology, and a full discussion of the technical aspects of karst hydrogeology is beyond the scope of this guidance. A basic understanding of the geologic and hydrologic regimes that are unique to karst aquifers, however, can provide useful insight into expected conditions.

The distinguishing characteristic of karst aquifers are large-scale conduits resulting in anisotropic flow pathways that are capable of transporting water over long distances in relatively short amounts of time. Carbonate aquifers can be classified (Table A-1), generalizing the hydrologic conditions and the types of conduits (caves) likely to be present (White. W.B. 1969). Table A-1 can be used to initialize a site-specific CSM by identifying features and flow regimes that may be present given the base conditions.

From the geochemical perspective, there is constant chemical interaction between the groundwater and rock. The slower groundwater moves through the rock, the more time minerals have to dissolve out of the rock and into the groundwater. However, with time, the water also becomes more saturated with the soluble ions and the reaction slows.

When groundwater flows preferentially in fractures, the interaction changes. Increased flow causes disequilibrium as the groundwater is more rapidly replaced and the water/rock residence time is decreased. In karst, the more soluble the rocks, the more the fractures become enlarged as the rock dissolves. As the fractures enlarge, the groundwater flow rates and volumes increase, allowing for more rapid dissolution and even physical erosion. This process is the basic mechanism for development of a karst aquifer.

The resulting architecture of the karst aquifer makes this environment problematic for investigators. The primary porosity of the rock matrix is usually unimportant as a flow mechanism and storage potential, while the secondary porosity, composed of the solutionally enlarged fractures and conduits, becomes the primary water transport and storage medium. Predicting the orientation, size, and interconnectivity of the solutionally enlarged fractures is the biggest challenge in characterizing the flow of groundwater through a karst aquifer.

Table A-1. Hydrologic classification of carbonate aquifers (White. W.B. 1969)

Table X-1. Hydrological Classification of carbonate aquifers (From While, 1969)

Flow Type	Hydrological Control	Associated Cave Type
DIFFUSE FLOW	GROSS LITHOLOGY Shaley limestones; crystalline dolomites; high primary porosity	Caves rare, small, have irregular patterns
FREE FLOW	THICK, MASSIVE SOLUBLE ROCKS	Integrated conduit cave systems
Perched	Karst system underlain go impervious rocks near or above base level	Cave streams perched, often have free air surface
Open	Soluble rocks extend upwards to land surface	Sinkhole inputs; heavy sediment load; short-channel morphology caves
Capped	Aquifer overlain by impervious rock	Vertical shaft inputs; lateral flow under capping beds; long integrated caves
Deep	Karst system extends to considerable depth below base level	Flow is through submerged conduits
Open	Soluble rocks extend to land surface	Short, tubular abandoned caves likely to be sediment-choked
Capped	Aquifer overlain by impervious rock	Long, integrated conduits under caprock, active level of system abandoned
CONFINED FLOW	STRUCTURAL AND STRATIGRAPHIC CONTROLS	
Artesian	Impervious beds that force flow below regional base level	Inclined three-dimensional network caves
Sandwich	Thin beds of soluble rock between impervious beds	Horizontal two-dimensional network caves

Fractured bedrock aquifers are anisotropic and heterogeneous—controlled by the size, orientation, and density of the fracture network. Karst aquifers are often characterized as combinations of three types of porosity present in the host rock: diffuse (matrix), fracture, and conduit. The karst aquifer can also be subdivided hydrostratigraphically into the epikarst, vadose zone, and phreatic zone. In more typical aquifers, the primary storage and transport of groundwater occurs primarily within the phreatic zone. However, the vadose zone, and often the epikarst, can play critical roles in the storage and transport of water, and more importantly, contaminants, through the karst landscape. A generalized schematic showing the relationship between porosity and hydrostratigraphy in karst aquifers is presented in Figure A-1.

Flow in conduits in the vadose zone mimicks a surface stream incised in a rock gorge, where the stream receives little input or output from diffusion. Inputs come from tributary conduits and flow is flashy and frequently turbulent. A mature karst aquifer is riverine, complete with meanders, cutoffs, sedimentation, and often subject to flash flooding and turbulent flow. In contrast, groundwater flow in conduits within the phreatic zone are most analogous to sewer systems and the resulting flow is often laminar.

Relatively young aquifers are dominated by small aperture fractures with limited interconnectivity. But with older, more developed systems, those fractures enlarge and become interconnected and complex, with the potential to transport large volumes of water over long distances. Mammoth Cave is a mature karst system with over 400 miles of mapped conduits (cave passages) that have been developing for an estimated 10 million years. As another example, groundwater has been traced through a complex conduit groundwater flow system originating in the central part of Slovenia, crossing under the Italian boarder and discharging from springs along the Mediterranean coast near the Italian city of Trieste. Some of the springs have the remnants of Roman bath houses still intact around them as a testament to the duration of groundwater discharge from the same location.

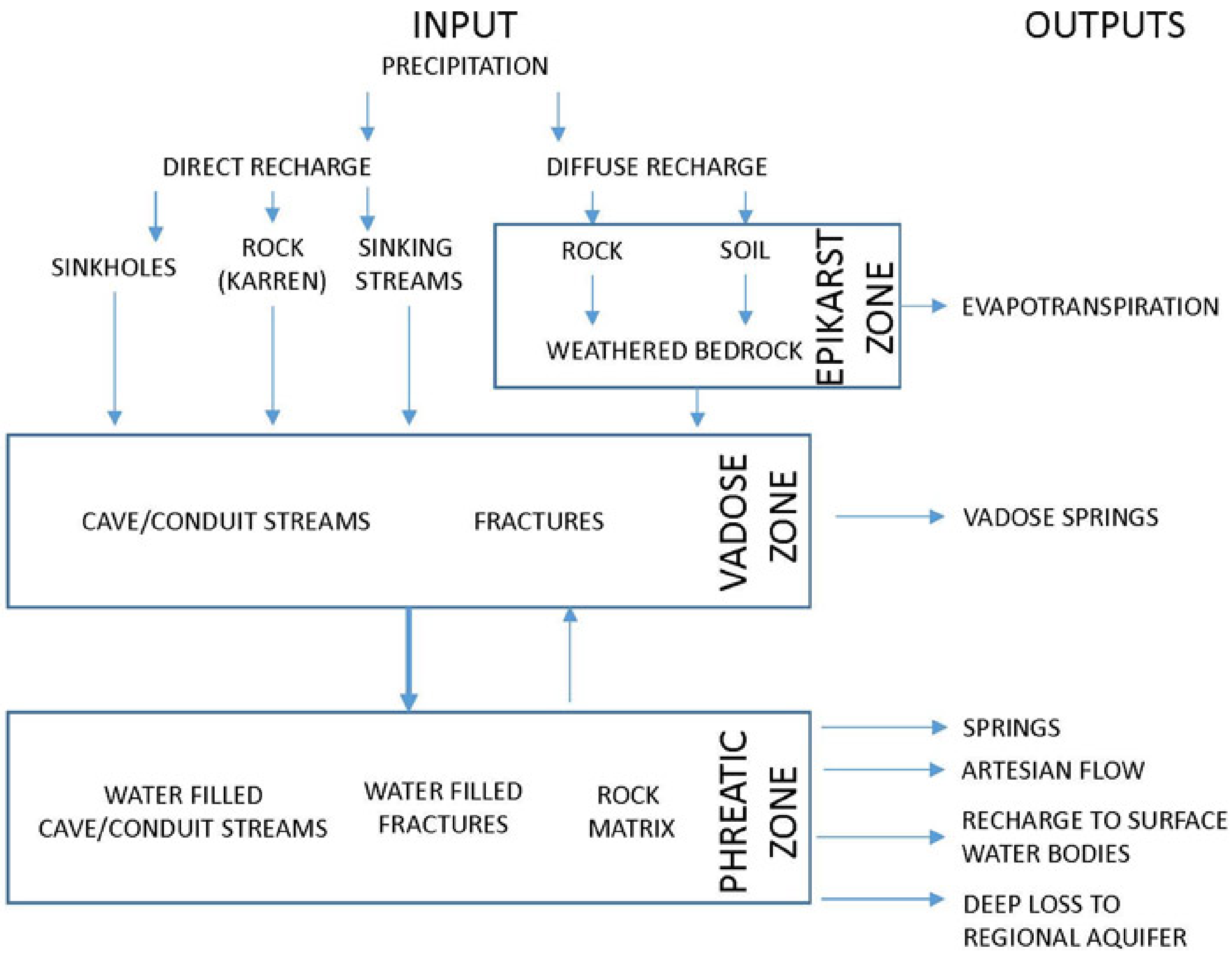


Figure A-1. A generalized flow diagram showing the primary pathways of groundwater movement through the different zones of a karst aquifer (Modified from (Ford 2007).

A.9. Karst Resources

Various agencies have attempted to compile records of karst features. GIS technology has allowed nongovernmental, regulatory, and other government agencies to compile spatial karst data for some specific regions that can be useful. These efforts, however, are piecemeal, often incomplete, and frequently difficult to locate.

One of the best sources for cave inventories is the local grottoes (clubs) of the National Speleological Society (NSS). NSS archives are primarily cave locations, but they often include cave maps, descriptions, and biological and archaeological inventories that can be useful. Multiple state level nongovernmental organizations, such as the Tennessee and Ohio Cave Surveys, inventory and maintain cave related databases.

Several karst research institutes include problem-solving as part of their mission. Resources in the United States include the National Center for Cave and Karst Studies, the Karst Waters Institute, the Hoffman Environmental Research Institute, and the Edwards Aquifer Authority. These institutions offer guidance, educational information, and support. A digital library for karst information from a variety of national and international sources is maintained at The Karst Portal. Researchers are encouraged to consult with these organizations when conducting karst investigations.

Response: connection of two normally divergent structures

Apppendix B. Bedrock Types

Knowledge of bedrock types is fundamental to understanding fractured rock aquifer systems and the terranes in which these systems occur. Bedrock types (igneous, sedimentary, and metamorphic) and the individual lithologies that occur within these groups directly influence primary porosity, secondary porosity (such as fractures), fracture characteristics (aperture, orientation, fabric, extent), and the physiography of an area or region. Physiography consists of the physical landscape and associated hydrology. This section provides a basic description of igneous, sedimentary, and metamorphic rock types and their subclassifications that are pertinent to fractured rock hydrogeology, groundwater contamination, and remediation.

B.1 Igneous

Igneous rocks are crystalline rocks that form from the cooling of magma or lava within the earth (intrusive igneous rocks), near the earth's surface (hypabyssal), or on the earth's surface (extrusive). Crystalline igneous rocks generally have three types of textures: aphanitic, phaneritic, and porphyritic (Figure B-1). Three additional textures are used with the extrusive igneous rocks, which are: glassy, vesicular and pyroclastic. Aphanitic textures consist of equigranular, small (fine-grained) crystals; phaneritic textures consist of equigranular, larger crystals (coarse-grained); porphyritic rocks consist of coarse crystals within a fine-grained groundmass.

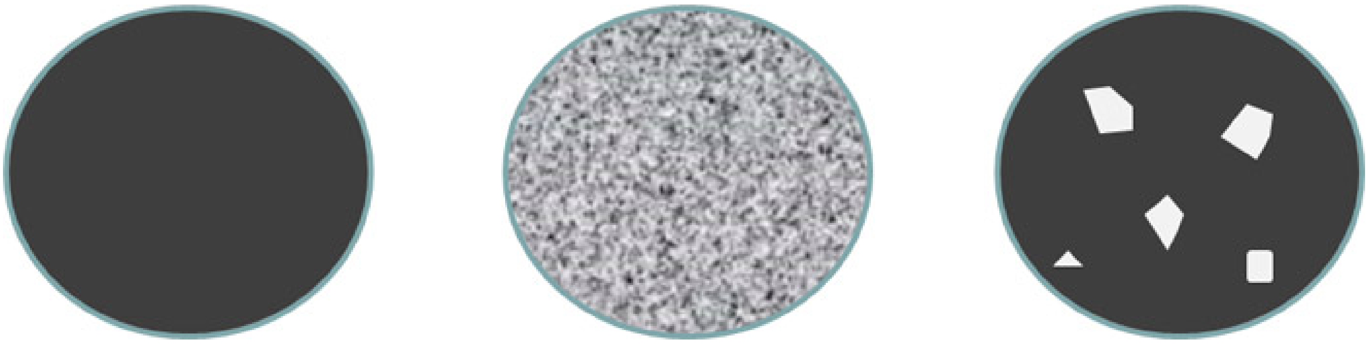


Figure B-1. Conceptual illustration of igneous textures, from left to right: aphanitic, phaneritic, porphyritic.

These equigranular or interlocking crystalline textures often result in fracture patterns that tend to be infrequent, discontinuous, nonuniform, random, or radial.

Glassy texture refers to a quick/rapid cooling lava that does not have an underlying organized mineral structure visible under a conventional polarized light microscope. Vesicular texture occurs when gases are trapped within a lava flow and minerals crystallize around the gas pocket. Pyroclastic texture results from explosive volcanic eruptions and the resulting rock is composed of a mixture of preexisting igneous rock, mineral grains, and ash particles. These three rock textures may be the most permeable of the igneous rock types, yielding zones of groundwater flow and may be the most susceptible to chemical weathering.

Igneous rocks are also characterized by their mineral and chemical composition ranging from felsic to mafic. Felsic rocks are enriched in quartz and feldspar, which consist of silicon, aluminum, sodium, and potassium. Mafic rocks are enriched in iron and magnesium-bearing minerals such as olivine and pyroxene.

Further discussion of intrusive and extrusive igneous rocks is provided below with emphasis on characteristics that influence physical and chemical hydrogeology.

B.2 Intrusive

Intrusive and hypabyssal igneous rocks are described together in this section, because they both crystallize beneath the earth's surface. These types of igneous rocks include massive intrusions such as plutons and tabular intrusions such as dikes (vertical to subvertical intrusion) and sills (horizontal to subhorizontal intrusion).

Plutonic igneous rocks derive from massive bodies of magma that have cooled slowly allowing mineral crystals to develop Figure B-2). The rate of cooling affects the size of the mineral crystals and the resulting texture. Consequently, plutonic rocks tend to have phaneritic texture with interlocking grains and little primary porosity. Plutonic rocks range in composition from felsic to mafic (for example, granite, diorite, and gabbro), which reflects the source of the magma and the timing of mineral crystallization. Mafic rocks are composed of minerals that are stable at higher temperature conditions and therefore make them more susceptible to weathering and erosion at near surface temperatures. The iron and magnesium content of mafic rocks may also make groundwater along water-bearing fractures susceptible to iron fouling of pumping and remedial systems. Conversely, a ready supply of ferric iron would be available to support microbial mediated biodegradation of some organic compounds. Felsic rock mineral assemblages tend to crystallize last under cooler temperatures and therefore are less susceptible to weathering at surface temperatures.

As erosion and uplift occurs, plutonic rocks experience decompression, which may result in radial, random, or dendritic type fracture patterns. Even at the ground surface, these plutonic igneous rocks may remain relatively massive, with few continuous fractures.

Figure B-2. Outcrop of granite pluton; generally massive with few fractures; some fractures in foreground.

Intrusive and hypabyssal rocks also include tabular intrusions such as vertical to sub-vertical dikes and horizontal to sub-horizontal sills (Figure B-3). These tabular intrusions can also range from felsic to mafic in composition (such as rhyolite, andesite, and basalt). Hypabyssal varieties of these dikes and sills experience shallow crystallization and tend to cool rapidly, resulting in an aphantic texture with the center of the intrusion being coarser grained due to slower cooling. The edge of the intrusion becomes finer grained because it cools quicker in contact with the country rock. The geometry of these intrusions has obvious implications for anisotropy and hydrogeologic boundary conditions. These dikes may be susceptible to erosion and cool in a tabular fashion, potentially resulting in planar fractures, especially in contact with country rock.

Figure B-3. Aphanitic, mafic intrusion into phaneritic pluton (granite); note thermal aureole in country rock (pink/orange discoloration surrounding mafic intrusion). Thermal aureole is susceptible to differential weathering and permeability.

B.3 Extrusive

Extrusive igneous rocks derive from the rapid cooling and crystallization of lava that has been extruded to the earth's surface (atmosphere or under a water body). The associated textures are also categorized by the chemical composition of the parent magma. Due to rapid cooling, extrusive igneous rocks tend to have an aphanitic or glassy texture. Associated with the aphanitic texture is the vesicular texture, which generally marks the top or base of a lava flow (Figure B-3). Extrusive igneous rocks tend to flow horizontally along the pre-existing ground surface and are characterized by layered stratification and textures that may include:

- tabular extrusion
- layered nonconformities (interbedded layers of extrusions and sediments)
- vesicular horizon
- weathered horizon

- weathered horizon intercepting vesicular horizon

Figure B-3 Aphanitic, mafic, extrusive igneous rock exhibiting multiple textures and porosity that may affect fluid occurrence and migration: fractures, vesicles, weathered horizon, weathered (interconnected) vesicles.

The variety of textures in extrusive igneous rocks tends to result in homogeneous permeability; however, the general horizontal nature of these extrusions can result in isotropic conditions in the horizontal plane. Columnar joints are unique to certain lava flows and hypabyssal intrusions, formed because of contraction of the lava with cooling, and the formation of polygonal joint partings perpendicular to the cooling surface. Surface water and groundwater can readily move along these joints and vesicular interflow zones. Pyroclastic textures are most like the clastic sedimentary rock type (discussed in the next section). Because they are associated with a volcanic eruption, however, the composition begins at high temperatures, so that after the rock particles and ash have deposited along low lying ground features, they may solidify together (for example, welded tuff). These rock types would not exhibit the same permeable features that a nonwelded tuff or other vesicular extrusive rock types may have.

B.4 Sedimentary Rocks

Sedimentary rocks are formed by either physical or chemical weathering of preexisting (precursor) rock formations. The sediment or dissolved matter are transported and deposited through physical, chemical, or organic processes. Once deposited, the sediment can become lithified by compaction, cementation, and recrystallization. Sedimentary rocks can be classified into textures based on the transport mechanism. Clastic textures are derived from physical weathering of the preexisting rock type and the sediment transported and deposited within a depositional environment. Clastic sedimentary rocks are further classified on the size of the resulting particles.

Nonclastic textures have undergone less transport and are formed in a depositional environment that generally contains a very small percentage of detrital silicate particles/grains. The nonclastic textures are generally subdivided by whether the main constituents are organic (organism or plant) or organically-derived (biologic or mechanical abrasion of organic material/clasts) or are inorganic mineral assemblages. The depositional environment provides a basis for initial interstitial water geochemistry and provides clues as to whether marine or fresh water conditions prevailed and whether these were aerobic or anaerobic to understand what minerals may have been more stable.

The clastic and nonclastic organic sedimentary textures include matrix-supported and grain-supported fabrics, which reflect porosity and potential permeability properties at the time of deposition. Grain-supported fabrics consist of larger grains that are in contact with one another with the potential of finer grained material in the interstitial space. Porosity and permeability can be high in this type and decrease with an increase of interstitial fine grains or cement filling in the void space. A matrix-supported fabric consists primarily of fine-grained sediments with a few coarse fragments that generally do not touch. If the grain size and composition is similar (such as a uniform sand), porosity and permeability can be high, but with compositional variety and finer grain size, permeability may decrease. According to Blatt (Blatt 1980):

The original porosity and permeability of sedimentary material changes continually through time in response to changes in subsurface stress fields, temperature and the chemical composition of underground waters.

B.4.1 Clastic

Clastic sedimentary rocks consist of rock fragments and minerals that are derived from physical and chemical weathering of other preexisting rock types (igneous, metamorphic, or sedimentary). Clastic sedimentary rocks range from fine-grained to coarse-grained depending on the size of the particles (clasts). The composition of the rock type provides some insight into the distance traveled from the parent source, with more resistant minerals remaining (for example, quartz) and less resistant minerals weathering and particle size decreasing with distance traveled.

Once deposited, the grain size and the particle shape affect the primary porosity. Smaller particles and clay minerals can be packed closer together and the resultant pore sizes are smaller and potentially more tabular, with a resultant orientation more parallel to bedding. Larger equal-sized grains exhibit a grain-supported fabric preserving the depositional porosity between these grains. Lithification of the sediments can decrease the initial porosity by either compaction affecting the finer grained sediments more or cementation of a new mineral in the existing pore space (interstitial cement). Common cements include calcium carbonate, silica, and ferric oxyhydroxide or ferrous carbonate. Many of the clastic sedimentary rocks are permeable and receive and transmit groundwater which has migrated from other rock types. Besides the process of cementation, ion-exchange may take place along a mineral surface, thus affecting the chemistry of the interstitial water. The fine grained clastic rocks, such as a siltstone or shale are characterized not only by the particle size but also by having a greater percentage of clay minerals. These rock types are porous and can hold water, which may reflect the original depositional environment, but do not transmit this water readily because the interstitial spaces are small and poorly interconnected (USGS 1992).

B.4.2 Nonclastic

Nonclastic texture indicates that the clasts or minerals that make up the rock have undergone little transport, generally were deposited in situ (within the basin of deposition). They can be subdivided into two groups based on the origin of the sediment: organic or inorganic.

Nonclastic organic rocks are formed in place within a depositional basin that is lacks an influx of detrital silicate particles and are comprised mainly of calcium carbonate minerals (calcite and dolomite) or original plant material (peat, lignite to bituminous coal). A variety of organic grains can be found in these rock types and depend on the depositional basin in which they formed. With lithification, these rocks undergo a complex series of replacement or recrystallization of the original grains or organic mud-sized particles. As with the clastic texture, the size of the grains and the mixture of grain sizes affect the primary porosity of the sediment. With lithification, the original porosity may decrease due to compaction, cementation within any void spaces or recrystallization of the original minerals.

Nonclastic inorganic rocks are formed in-place within unique depositional environments and are further classified based on the mineral present (mineralogy). These rocks tend to be composed of interlocking coarse to fine-grained crystals and generally have low primary porosities. Examples include: rock salt, rock gypsum, travertine (calcite), dolomite and chert (microcrystalline quartz).

B.4.3 Secondary Porosity

Once sediments, from both the clastic and nonclastic rock types, are lithified and have become new sedimentary rocks, they may have preserved original depositional features such as ripple marks, mud cracks, cross-beds, bedding planes and erosional discontinuities. These features, especially bedding planes, may be significant to the occurrence of and migration of groundwater and contaminants.

The nonclastic inorganic rocks are not as brittle and tend to deform (or exhibit solid-phase flow) parallel to the bedrock contacts they are adjacent to. Joints, folded or tilted bedding and fault planes can be the dominant avenue for fluid migration and interaction of the bedrock with this fluid. For some rock types, in-particular the nonclastic organic (or carbonate rocks), this interaction between groundwater and the carbonate rock may result in chemical weathering (dissolution and precipitation), enlarging the joints, fractures and bedding plane partings and result in a unique topography classified as karst.

Both clastic and nonclastic organic rocks that are exposed to tectonic forces resulting in structural deformation exhibit joints, inclined and folded bedding, and faulting.

B.4.4 Structural and Bedding Characteristics

Sedimentary rocks that are deposited in a basin and do not experience structural deformation through tectonic forces tend to be homogeneous and isotropic in the horizontal plane or parallel to bedding. Clastic sedimentary rocks that are exposed to tectonic forces, resulting in structural deformation, which results in inclined and folded bedding (Figure B-4) and faulting (Figure B-5). These structural characteristics result in significant anisotropy and hydrogeologic boundary conditions, which are often measureable and predictable at the area to regional scale.

Figure B-4. Inclined sandstone bedding on flank of NE-SW striking anticline, resulting in preferential flow direction (anisotropy) and hydrogeologic barrier condition.

Figure B-5 Vertical and thinly bedded siltstone striking N-S orthogonal to E-W potentiometric gradient.

B.5 Metamorphic

Metamorphic rocks are derived from other rock types (such as igneous, sedimentary, and older metamorphic) that are subject to heat and pressure due to tectonic forces, deep burial of sedimentary basins, and high temperatures from magma bodies or extruded flows. Like igneous rocks, metamorphic rocks are also crystalline, but exhibit growth of crystals by chemical reactions with other minerals and fluids in the parent rock of mineral suites that are more stable under the new pressure and temperature conditions. These mineral crystals can change in shape and size, and become deformed or reoriented in a different direction.

Two major textures of metamorphic rocks reflect the dominant change of either increased pressure or temperature or both from the pre-existing conditions (prior to metamorphism): foliated and nonfoliated. Foliated texture means that the rock exhibits foliation (oriented layering) that occurs orthogonal to the principal direction of compression/pressure and is most obvious with elongate mineral grains. Nonfoliated metamorphic rocks lack foliation and may have been more influenced by increased temperatures; however stretched and deformed rock and fossil fragments indicate tectonic forces may be present. Consequently, metamorphic rocks generally have low primary porosity and permeability, and exhibit physical characteristics that are similar to igneous and sedimentary rocks with regard to texture, orientated fabrics, and development of fracture patterns relevant to fluid (groundwater and contaminant) occurrence and migration.

B.5.1 Foliated

Foliated metamorphic rocks are characterized by a layered, platy, or banded orientation to the minerals that comprise the rock. This configuration imparts a foliation (directional layered fabric) to the rock, which is observed at multiple scales: microscopic, hand sample/core, outcrop, site, and regional terrane. This fabric is also referred to as schistosity. Like sedimentary bedding, foliation has a structural orientation and can exist as secondary porosity between layers, resulting in anisotropy. Foliated metamorphic rocks in order of increasing foliation include slate, phyllite, and schist. The following figures (B-6, 7 and 8) illustrate textures and foliation associated with schist, a strongly foliated metamorphic rock type.

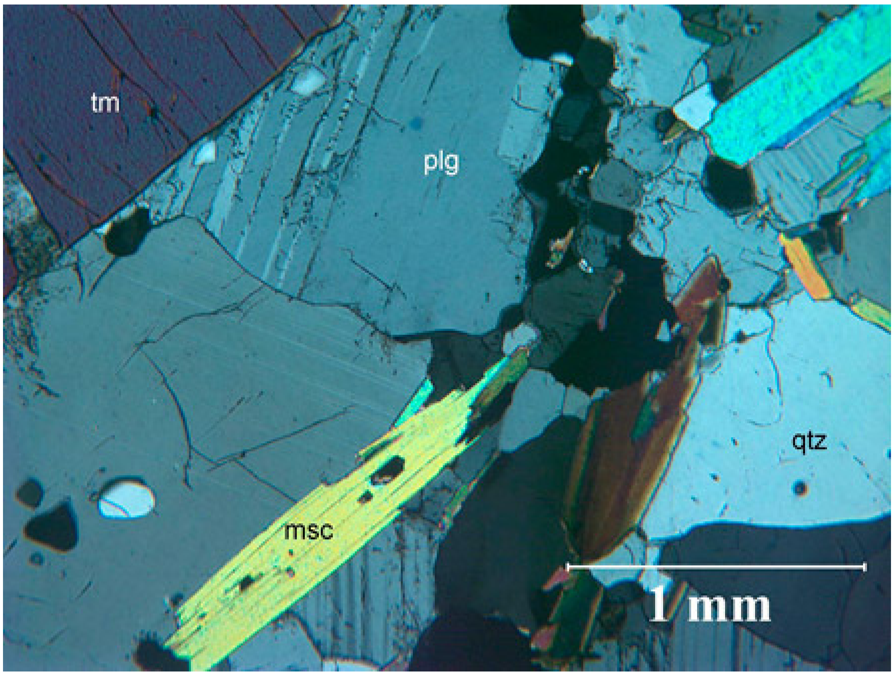


Figure B-6 Photomicrograph of schist exhibiting fused grains with little primary porosity and orientated/platy minerals (muscovite, biotite, tourmaline).

Figure B-7 Foliated schist in outcrop.

Gneiss is a foliated metamorphic rock that exhibits banding of mineral layers, but not a platy foliation that would strongly influence groundwater flow as secondary porosity and anisotropy. The texture of gneiss tends to be like that of intrusive igneous rocks, relatively large and equigranular crystals that are fused with little primary porosity.

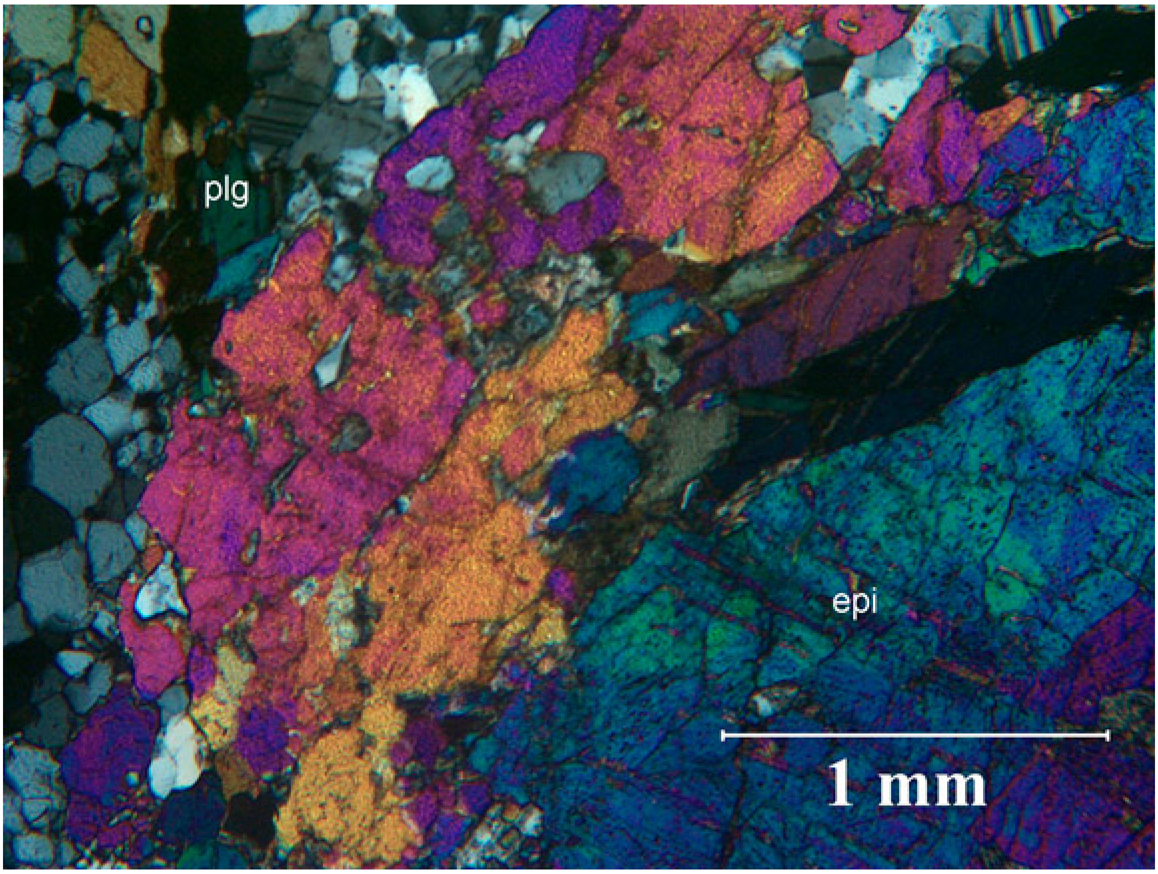


Figure B-8 Photomicrograph of gneiss exhibiting relatively large and fused grains/crystals.

B.5.2 Nonfoliated

Nonfoliated metamorphic rocks do not exhibit an oriented fabric and are subdivided on the composition of the original parent rock. These rocks include marble and anthracite coal. Marble is a metamorphosed carbonate rock and tends to be crystalline with little foliation and likewise, anthracite coal is metamorphosed bituminous coal and exhibits a conchoidal fracture. Both rock types exhibit little primary porosity.

Table B-1. Terrane analysis matrix

Click Here to view Table B-1 in Adobe Acrobat format.

Printed from: Interstate Technology & Regulatory Council (ITRC). 2017. *Characterization and Remediation of Fractured Rock*. FracRx-1. Washington, D.C.: Interstate Technology & Regulatory Council, Characterization and Remediation of Fractured Rock, http://fracturedRx-1.itrcweb.org.

Appendix C. Drilling

Choosing a drilling method to install a well for site characterization and remediation at a fractured rock site is based on the following considerations:

- an understanding of the relative advantages and disadvantages of various drilling methods
- the site conceptual flow model
- the monitoring and remediation program objectives
- the drilling and borehole data collection process
- monitoring or remedial well design

An overarching principle guiding the use of any drilling method at a fractured rock site is the prevention vertical cross contamination through the simple act of drilling a borehole. A contamination source is typically at the surface or in the shallow subsurface. An open borehole in bedrock is an unnatural condition whereby zones with different water level elevation, which are normally separated by rock, are interconnected thereby allowing water and contaminants, to flow vertically downward. The drilling process must be conducted in such a way as to prevent, or limit, the potential for the borehole to act as a vertical conduit for contamination to move from shallow to deeper zones in the fractured rock and thereby spread contamination and make characterization and remediation more difficult.

C.1. Drilling Methods

The drilling methods typically used at fractured rock sites include: air rotary, rock core, water or mud rotary (using a tricone bit), and sonic. All drilling methods use a drilling fluid to cool and lubricate the drill bit and, if necessary, to maintain borehole stability and carry cuttings from the bottom of the borehole to the surface. When drilling in unconsolidated sediments, water-based drilling fluid or casing advance methods are typically used to keep the borehole open by countering hydrostatic forces in the formation.

Water-based drilling fluid is prepared by mixing water with an additive, typically powdered bentonite, a polymer, or both to increase the weight and viscosity of the fluid to facilitate cuttings removal. If a well is to be installed in the weathered bedrock zone (saprolite, the transition between the overburden and bedrock), then a water-based drilling fluid or a casing advance method typically must be used to maintain borehole stability. A casing may be advanced while drilling using either a rotary or sonic drilling method. In bedrock, the borehole stays open without the support of a water-based drilling fluid or a casing. Consequently, drilling methods which use air or water without additives as the drilling fluid are preferred because they facilitate using borehole for data collection prior to well construction and make well development more efficient, ensuring better communication between the well and formation.

The air rotary method uses air, often with some water added to control dust, as the drilling fluid. The air rotary method is relatively fast compared to other methods and is therefore often the most cost effective. Rock coring uses water as a drilling fluid and produces rock core suitable for logging and characterization, but is relatively expensive. The rotary drilling method can be conducted using water alone as the drilling fluid. However, use of drilling mud is often required to ensure adequate removal of cuttings. Likewise, the sonic method uses water, often with some bentonite added, as the drilling fluid to cool and lubricate the bit (cuttings are pushed to the side and rock ahead of the casing is removed with a core barrel). Because the drill bit is attached to the bottom of the casing, the sonic method also advances a casing as the borehole is advanced. The sonic drilling method provides a rock core as the borehole is advanced however the core is often broken up so rock coring using a diamond core bit is preferred if rock core is required for logging, sampling, or other characterization work. The cable tool method may also be used. This method uses drilling mud, but has the advantage of being able to advance a borehole under the most difficult drilling conditions.

Finally, the source of water using during drilling must be carefully selected and must be analyzed for all site related contaminants prior to use.

C-2. Site Conceptual Model and Well Location

The site conceptual model provides valuable information required to plan the drilling program such as overburden and saprolite thickness, the type of rock underlying the drilling location, and the physical properties of the rock including the orientation of features such as joints and bedding. In addition, the target depth of the borehole is based on the conceptual flow model. Conversely, data collected during the drilling program is used to update, refine, and expand the conceptual flow model.

C.3. Monitoring and Remediation Program Objectives

Monitoring and remediation program objectives must be taken into consideration when selecting a drilling method for a given well. The first consideration is whether samples will be collected as the borehole is advanced and if data will be collected as the borehole is advanced or after the borehole is completed, but before the well is installed. This step is often necessary to achieve project objectives such as determining the extent and nature of contamination, collecting data on borehole transmissivity and feature orientation, and, at a minimum, data needed to design the well such as the location of transmissive zones. Borehole diameter is an important factor for project objectives. For example, most borehole geophysical methods work best in borehole between about 4 inches and 8 inches in diameter.

C.4. Drilling and Borehole Data Collection Process

The borehole drilling and well installation process must be conducted to meet project objectives, as follows:

- preventing unconsolidated or weathered bedrock (saprolite) from collapsing into the borehole
- preventing vertical migration of contaminants, including DNAPL, from the overburden, or shallow bedrock, deeper into the bedrock
- collecting data needed for site characterization and well design from the rock core or open hole
- completing the well successfully

For example, if the site is underlain by overburden, this region is typically cased off by advancing a borehole three to five feet into competent rock, installing a steel casing into the borehole, grouting the casing in place, and then allowing the grout to set before the borehole is advanced into bedrock. Because a well will not be installed in the overburden or weathered bedrock section of the borehole the full range of drilling methods may be used to install the casing, including those which use water/bentonite drilling fluid. The critical decision is the diameter of the casing because this distance controls the diameter of the borehole and well which can be installed in the fractured rock. For example, if a Westbay multilevel system or a 2-inch diameter screened well is being installed then a 4-inch casing may be sufficient because it will allow a 3 7/8-inch borehole to be drilled into bedrock. On the other hand, if a 4-inch diameter screened well or Water FLUTe is being installed, then a 6-inch diameter or 8-inch diameter casing would be required. Steel casing is typically used. If there are contaminants such as DNAPL present in the shallow bedrock, then this region may also be cased off before the borehole is advanced deeper into fractured rock.

Once the overburden and weathered rock are cased off, a borehole maybe advanced to depth using rock core to characterize rock lithology and to obtain samples for analysis of physical and chemical properties of the rock matrix and contaminants in the rock matrix. Alternatively, well screen or sampling zone placement may be determined by the depth to a specific lithologic unit best identified in rock core. At other locations where rock sampling is not required and logging from cuttings is sufficient to meet project objectives (precise lithologic control is not required), the borehole may be advanced to depth using air or water rotary methods.

C.5. Monitoring or Remedial Well Design

Using the results of the data collected during the drilling project, monitoring or remedial well designs are completed and the wells are installed. Three types of wells are commonly used for monitoring and site remediation at fractured rock sites: multilevel wells, screened wells, and open-hole wells. The design of each type of well influences the choice of drilling method. For example, if a multilevel well is selected for installation then rock coring should be considered as the drilling method because it provides a smooth borehole wall, compared to the air rotary method. A smooth borehole well facilitates a good packer or liner seal. If a conventional screened well or open-hole well is required, then the air rotary or water rotary method is typically used because it is less expensive than rock coring. Finally, wells must be constructed in accordance with any state or local regulatory requirements including but not limited to materials (such as grout recipe), borehole diameter, annular space, and maximum open or screened interval length.

In some cases, such as the installation of a screened monitoring well, the design may be completed or finalized in the field and the well installed immediately after (the same day) drilling is completed. In contrast, if multilevel wells are installed, data collected from the borehole must be compiled and analyzed, the design completed, the well fabricated, and then the materials, equipment, and personnel must be mobilized to the site so that well construction can be completed. This process takes weeks to complete and during this time it is important the borehole be lined to prevent vertical fluid movement in the borehole.

C.6. Equipment Decontamination

Before first use at a site and after drilling and well installation at each location is completed, all downhole equipment and equipment in contact with groundwater must be thoroughly decontaminated to remove contaminants in accordance with the approved project plan.

Appendix D. The 21-Compartment Model

The 21-Compartment Model is a representation of the CSM at an appropriate level of resolution for communicating the occurrence and distribution of contamination, and can help in making decisions for successful characterization, design, and ultimately remediation toward site remedial objectives. The 21-Compartment Model is intended primarily for fractured bedrock under saturated conditions and can be applied at various stages of characterization and remediation, including, but not limited to:

- communicating the distribution of an individual contaminant or nonaqueous phase liquid (NAPL) between less transmissive (such as rock matrix porosity) and more transmissive zones (such as fractures/bedding planes) within the source zone and down gradient from the source zone
- providing an organized framework to assess contaminant mass flux between the source zone and down gradient from the source zone, and between relevant compartments within the source and down gradient regions
- communicating the distribution of an individual contaminant or NAPL over time between less transmissive and more transmissive zones, and between the source area and down gradient from the source area
- identifying data gaps in site characterization or the remedial investigation
- establishing SMART functional objectives for remediation
- screening remediation technologies
- communicating the rationale for monitoring within the source zone or down gradient from the source zone (whether to monitor more transmissive zones, or to monitor for potential rebound from the matrix, or back-diffusion).

Visual models, based on site characteristics, provide a logical and fundamental basis for discussion and understanding among all parties involved during the development of a remedial strategy. After the initial compartments are filled in with what is known about the site, the need for more characterization to develop an accurate and usable model for decision-making is often the next step. This model is also useful for presentation of site-specific remedial concerns to other interested parties and stakeholders. The 21-Compartment Model, is not a replacement for the CSM but rather a tool that can be used in conjunction with, and help communicate key elements of, the CSM.

For contaminant mixtures in the 21-Compartment Model, such as chlorinated solvents and fuels (such as gasoline or diesel), these can occur in four phases in the source zone (DNAPL or LNAPL, aqueous, sorbed, and vapor) and three phases in the plumes (per NRC 2005, there is no DNAPL or LNAPL in plumes). Each of these phases can occur in subsurface zones that can be classified as “transmissive” (mobile) or “lower permeability” (immobile).

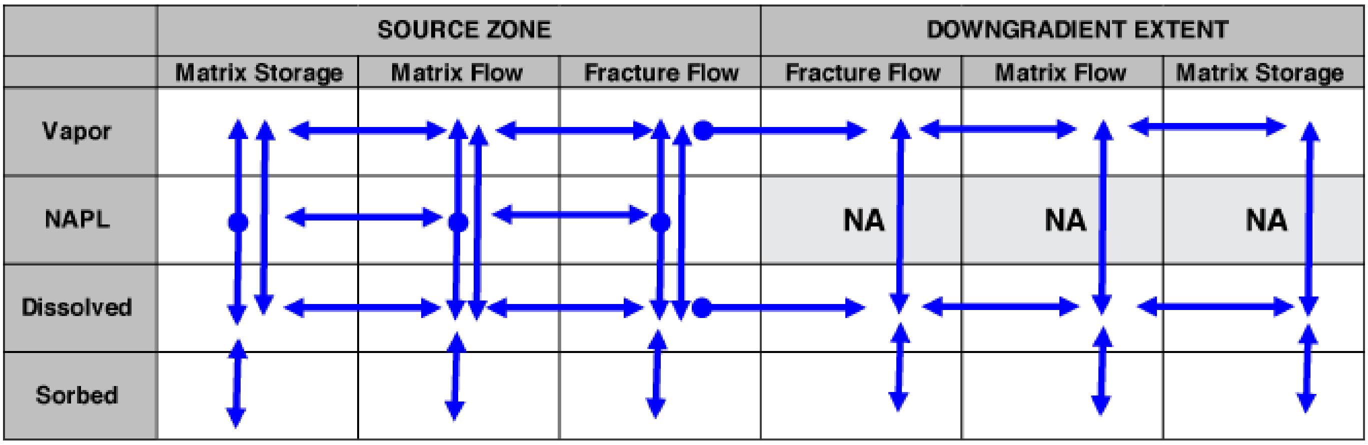
Table C-1 shows the 21-Compartment Model in blank tabular form. One way to use the 21-Compartment Model is to use qualitative estimates, or ranges, of the potential chemical concentration (or potential) in each compartment as relevant to a particular site. Colors may additionally be assigned to the ranges. Then, mass transfers between compartments can be anticipated as contaminants flow from zones of higher chemical potential to zones of lower chemical potential. The transfers may be advective or diffusive. Table C-2 shows the transfers that are possible among the various compartments.

Table D-1. The 21-Compartment Model in blank tabular format

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor*						
NAPL*				NA	NA	NA
Dissolved						
Sorbed						

*Would not apply to contaminants (such as metals) for which there is no liquid or vapor phase.

Table D-2. The 21-Compartment Model with common contaminant fluxes between compartments (Solid arrows are reversible fluxes; dashed arrows are irreversible fluxes.)



Note that flux lines shown are intended to convey the qualitative direction of flux, but not the quantitative value of the flux

In the Integrated DNAPL Source Strategy (ITRC 2011) guidance, a 14-Compartment Model, for application to unconsolidated media, was introduced. For a more thorough discussion for how the 14-Compartment Model, and by extension this 21-Compartment Model can be applied, refer to that document. This document highlights a few key applications of the 21-Compartment Model for saturated fractured bedrock, including applying the 21- Compartment Model to development of the CSM for a contaminated fractured bedrock site, and an example for using the 21-Compartment Model to screen remedial technologies for sites with contaminated saturated fractured bedrock. The examples shown are mostly sites with DNAPL release to illustrate the use of the 21-Compartment Model, but the same concepts can be applied to individual contaminants or to other mixed contaminants such as LNAPL, based on their unique fate and transport characteristics.

D.1 CSM and the 21-Compartment Model

After generating an initial CSM for a bedrock site, but prior to performing site characterization, the 21-Compartment Model can be applied to further develop the CSM in subsequent iterations, and then be used as a tool during remediation alternative screening. The 21-Compartment Model applies generally to three common fractured bedrock settings: uncemented sandstone, shale, and granite. In these settings, a contaminant mass may be distributed among the various compartments and the mass distribution can change over time, which can be taken into account in the site characterization objectives. The 21-Compartment Model may then be revisited following the site characterization and refinement of the CSM to determine how the site understanding may have changed because of characterization activity.

Table D-3a fills in the 21-Compartment Model to represent a hypothetical site underlain by uncemented sandstone just after a DNAPL spill occurred. At this stage, the chemical potential in the DNAPL phase is high, and there has been little mass transfer into other compartments. At this early stage of spill site maturation, the mass transfers are primarily from the DNAPL into other compartments. Note for uncemented sandstone that contaminant mass is shown to be present in matrix storage and fracture flow, but also to be present in matrix flow (flow through the relatively porous/transmissive rock matrix associated with uncemented sandstone).

In transmissive zones (within secondary porosity features such as fractures and bedding planes) aqueous- or vapor-phase contaminants (here, chlorinated solvents) are carried with the flow of water or soil gas. In contrast, low-permeability zones (primary porosity) are largely stagnant from a flow perspective. Critically, low-permeability zones store and release contaminants via diffusion (Freeze 1979; Sudicky 1986; Parker 1994; Chapman 2005; Sale 2008).

Table D-3a. The 21-Compartment Model for the early-stage DNAPL spill site underlain by sedimentary bedrock (uncemented sandstone).

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	Medium	Medium	Medium	Medium	Low
NAPL	Low	Low	High	NA	NA	NA
Dissolved	Low	Medium	Medium	Medium	Medium	Low
Sorbed	Low	Low	Medium	Medium	Medium	Low

Table D-3b shows the same hypothetical site underlain by uncemented sandstone, but after a period where the contaminants, and in particular the DNAPL, have partitioned to other compartments. This is a middle stage representation characterized by an absence of DNAPL, and increase dissolved phase concentrations. In addition, this middle stage is characterized by matrix diffusion whereby high dissolved concentrations are diffusing into the rock matrix, which later acts as a reservoir of sustained dissolved contamination through back-diffusion.

Table D-3b. The 21-Compartment Model for the mid-stage DNAPL spill site underlain by sedimentary bedrock (uncemented sandstone).

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Medium	Medium	Medium	Medium	Medium	Medium
NAPL	Medium	Medium	Medium	NA	NA	NA
Dissolved	Medium	Medium	Medium	Medium	Medium	Medium
Sorbed	Medium	Medium	Medium	Medium	Medium	Medium

Table D-3c shows the same hypothetical site underlain by uncemented sandstone, but after a longer period where the contaminants, and in particular the DNAPL, have partitioned to other compartments, and high concentrations of dissolved contaminant have attenuated. This late stage is characterized by an absence of DNAPL and a decrease in previously high dissolved phase concentrations. This late stage is also characterized by back-diffusion, with dissolved concentrations diffusing from the rock matrix back into fractures, which may sustain concentrations above cleanup levels.

Table D-3c. The 21-Compartment Model for the late-stage spill site underlain by uncemented sandstone.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	Low	Low	Low	Low	Low
NAPL	Low	Low	Low	NA	NA	NA
Dissolved	Low	Low	Low	Low	Low	Low
Sorbed	Low	Low	Low	Low	Low	Low

Tables D-4a through D-4c illustrate the same three stages as applied to a site underlain by shale bedrock. Note for shale bedrock that matrix flow is not present, and these compartments are shaded out as not applicable. Otherwise the progressive partitioning of contaminant mass is similar over time to the uncemented sandstone.

Table D-4a. The 21 Compartment Model for the early-stage DNAPL spill site underlain by shale.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	NA	Medium	Medium	NA	Low
NAPL	Low	NA	High	NA	NA	NA
Dissolved	Low	NA	Medium	Medium	NA	Low
Sorbed	Low	NA	Medium	Medium	NA	Low

Table D-4b. The 21 Compartment Model for the mid-stage DNAPL spill site underlain by shale.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Medium	NA	Medium	Medium	NA	Low
NAPL	Low	NA	Medium	NA	NA	NA
Dissolved	Medium	NA	Medium	Medium	NA	Low
Sorbed	Medium	NA	Medium	Medium	NA	Low

Table D-4c. The 21 Compartment Model for the late-stage spill site underlain by shale.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	NA	Low	Low	NA	Low
NAPL	Low	NA	Low	NA	NA	NA
Dissolved	Low	NA	Low	Low	NA	Low
Sorbed	Low	NA	Low	Low	NA	Low

Tables 5a through 5c illustrate the same three stages as applied to a site underlain by granite bedrock. Note for granite bedrock that matrix flow is not present, and matrix storage is considered negligible. Otherwise the progressive partitioning of contaminant mass is similar over time as compared with the uncemented sandstone.

Table D-5a. The 21 Compartment Model for the early-stage DNAPL spill site underlain by granite.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Negligible	NA	Medium	Medium	NA	Negligible
NAPL	Negligible	NA	High	NA	NA	NA
Dissolved	Negligible	NA	Medium	Medium	NA	Negligible
Sorbed	Negligible	NA	Medium	Medium	NA	Negligible

Table D-5b. The 21 Compartment Model filled in for the mid-stage DNAPL spill site underlain by granite.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Negligible	NA	Medium	Medium	NA	Negligible
NAPL	Negligible	NA	Medium	NA	NA	NA
Dissolved	Negligible	NA	Medium	Medium	NA	Negligible
Sorbed	Negligible	NA	Medium	Medium	NA	Negligible

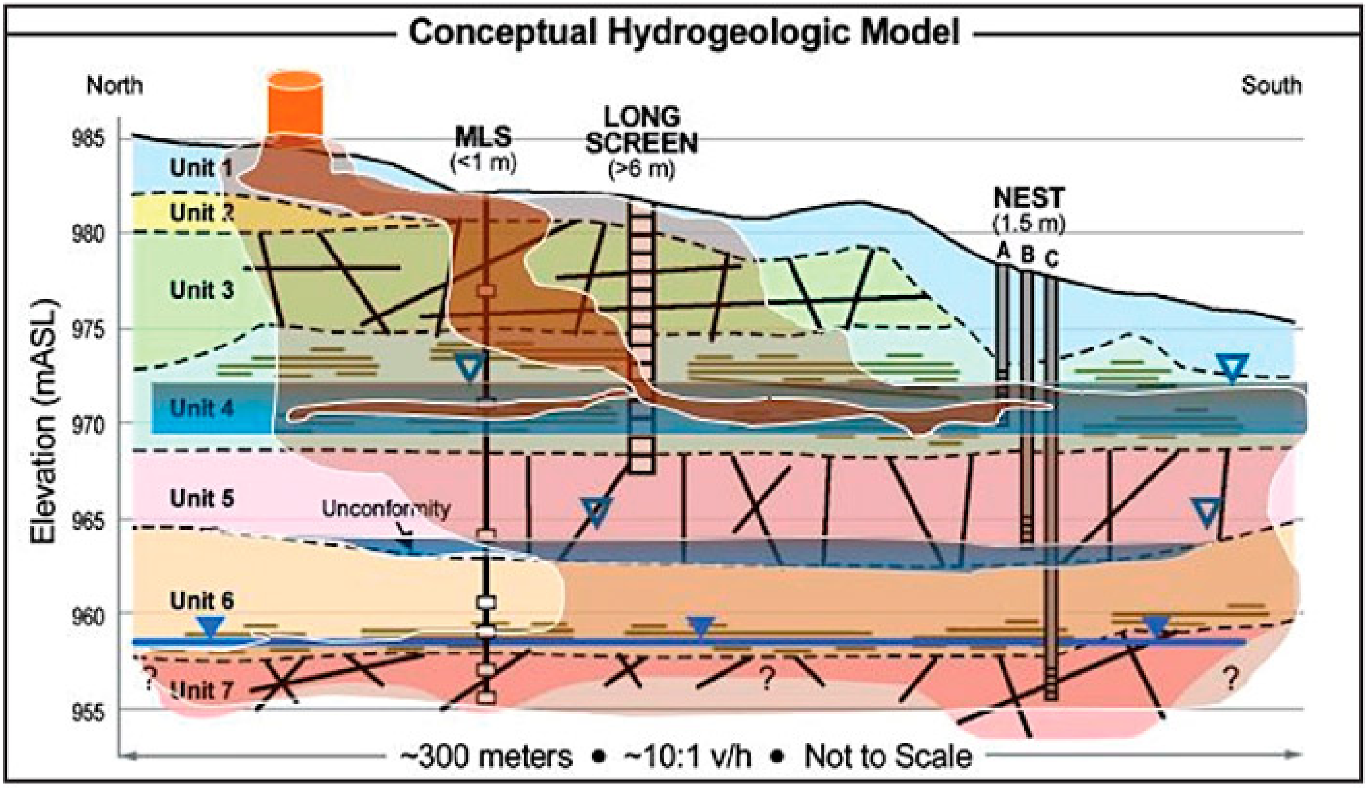
Table D-5c. The 21 Compartment Model filled in for the late-stage DNAPL spill site underlain by granite.

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Negligible	NA	Low	Low	NA	Negligible
NAPL	Negligible	NA	Low	NA	NA	NA
Dissolved	Negligible	NA	Low	Low	NA	Negligible
Sorbed	Negligible	NA	Low	Low	NA	Negligible

For both the sedimentary and igneous examples above, the transmissive zones of early stage plumes contain the highest VOC concentrations in their sources, particularity near the DNAPL phase. For sedimentary rock with significant primary porosity, over time the early-stage DNAPL phase, based on aqueous-phase equivalent concentration, is diminished by advection, biotic and abiotic degradation, and mass transfer into lower-permeability regions (the matrix porosity) and other chemical phases within the source as well as the plume. In a middle stage, the aqueous-phase equivalent concentrations across affected phases and zones are relatively equal. In late-stage plumes, contaminant concentrations have attenuated in the more permeable (transmissive) zones, and the larger remaining concentrations (again only in the sedimentary bedrock example, but not the case with the granite example that has little or no appreciable matrix porosity) remain in the lower-permeability zones within both the source and the plume.

These concepts are a useful tool to develop objectives for site characterization planning and ultimately can be revisited and refined as with the CSM for later remediation and monitoring.

After completing the site characterization, and subsequently refining the CSM, the 21-Compartment Model can be revisited and refined for better decision making. Figure D-6 shows an example of what the 21-Compartment Model might look like following site characterization and refinement of the CSM. For this example, a site illustration is superimposed above the 21-Compartment Model. The table below is filled in to present the CSM at level of resolution that can be communicated to those involved in project planning. Specifically, the first table below the site illustration shows the understanding of the relative distribution of contaminants after site characterization. An additional table presents an interpolation of where the contaminant mass may be over time. This version of the 21-Compartent Model can be used to communicate key information gained from the site characterization for use in decision making during remediation planning followed by monitoring.



CURRENT						
	Source Zone			Downgradient Extent		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor		low			low	
Napl		low		NA	NA	NA
Dissolved		low			low	
Sorbed		low			low	
5 - 10 YEARS						
	Low or Non Transmissive	Transmissive		Transmissive		Low or Non Transmissive
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor		low			low	
Napl		low		NA	NA	NA
Dissolved		low			low	
Sorbed		low			low	

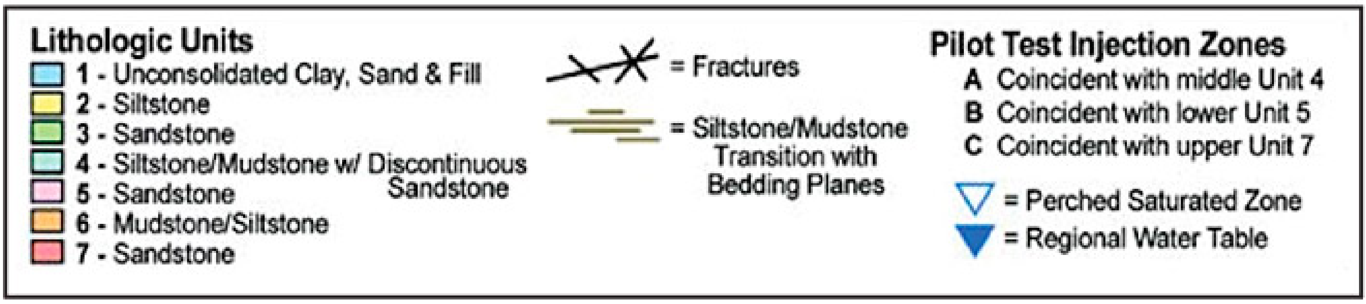


Figure D-6. The 21-Compartment Model combined with site illustration.

Source of Conceptual Hydrogeologic Model: Jim Studer, InfraSUR LLC 4/2/17.

D.2 Technology Screening with the 21-Compartment Model

The 21-Compartment Model presents features of the CSM that aid in understanding and communicating how contaminants are moving and changing over time between the different compartments. This model generally divides the source area and extent of dissolved contaminants into areas of high transmissivity (fracture flow, matrix flow) and areas of low relative transmissivity (matrix porosity). The 21-Compartment Model can also be used for screening alternative remedial approaches, or in the evaluation of individual technologies, and as a tool to communicate combined remedy strategies.

As illustrated in Figures D-7 and D-8 (a through d), the 21-Compartment Model can be applied to evaluating remedial objectives, and for technology screening and for the development and evaluation of alternative remedial approaches. A more quantitative approach to perform this evaluation was discussed in ITRC guidance (ITRC 2011) but is not repeated here. The qualitative approach is applied as follows:

1. Functional objectives are identified and illustrated using the 21-Compartment Model (Figure D-7). For this example, the first absolute objective is protection of human health by reducing the risk of vapor intrusion and the environment by reducing dissolved concentrations below cleanup levels.
2. The remedial strategy under consideration is source area treatment to reduce dissolved contaminant concentrations (PCE DNAPL in this example), which will result in attenuation of dissolved contaminant concentrations down gradient of the source area. The reduction in dissolved concentrations additionally reduces the vapor intrusion risk in the source area and ultimately downgradient from the source area.
3. A remedial approach employing pump and treat technology in the source area is screened first (Figure D-8a). Assuming adequate characterization and mapping of fractures, pump and treat has the potential to significantly reduce dissolved concentrations in the source area, particularly in relatively transmissive fracture flow zones (within the secondary porosity) of the fractured rock. However, even with adequate characterization and mapping of fractures and fracture flow paths, pump and treat may not be effective for addressing contaminant mass present within the matrix porosity of the rock. Upon termination of pump and treat operations, back-diffusion of contaminants from this matrix porosity compartment may result in rebound of dissolved-phase contaminants in groundwater in the transmissive fracture zones. This rebound could lead to an extended remediation life cycle and increased costs compared to more other technologies that may be more effective for contaminants in the rock matrix.
4. Figure D-8b illustrates screening of in situ chemical oxidation (ISCO) using a strong, but relatively short-lived oxidant such as catalyzed hydrogen peroxide. In this case, the strong oxidant can be effectively distributed through the relatively transmissive fracture zones but, due to the short oxidant lifetime, cannot penetrate the rock matrix to address the contaminant mass in the matrix storage compartment. The potential for posttreatment back-diffusion and for not meeting functional objectives can resemble that of pump and treat.
5. Figure D-8c illustrates the screening of ISCO using a longer-lasting oxidant, such as permanganate. In this case (as again assuming adequate characterization and mapping of fractures and groundwater flow paths), the oxidant may effectively destroy contaminants within the transmissive fractures. In addition, due to the longer lifetime of the oxidant and associated chemical gradients, the oxidant persists and can itself diffuse into the matrix porosity. The result may be effective treatment of contaminants in both the transmissive and nontransmissive zones of the fractured rock source area, resulting in mitigation of indoor vapor risks and down gradient dissolved concentrations as therefore meeting the functional objectives more effectively.
6. Figure D-8d illustrates screening of a thermal remediation technology, such as in situ thermal desorption or electrical resistivity heating, for source area treatment. As with the alternative approach using a strong and long lasting ISCO reagent, this alternative also offers the potential to address contaminants in both the transmissive fracture zones as well as less transmissive zones (matrix porosity). Again, the result may be effective treatment of contaminants in both the transmissive and nontransmissive zones of the fractured rock source area, resulting in mitigation of indoor vapor risks and downgradient dissolved concentrations as therefore meeting the functional objectives more effectively.

In this example, the selection of either a strong and long lasting ISCO reagent, or the use of thermal remediation technology, may be able to meet the functional objectives. Other site-specific factors need to be considered before ultimately selecting the remedial approach for a site, but the use of the 21-Compartment Model provides insight into the potential effectiveness, strengths, and weaknesses of individual remedial approaches.

Figure D-7. Identification of functional objectives for remedial approach (uncemented sandstone impacted by an early- to midterm release of PCE DNAPL).

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Medium	Medium	Medium	Medium	Medium	Low
NAPL	Medium	High	High	NA	NA	NA
Dissolved	Medium	Medium	Medium	Medium	Medium	Low
Sorbed	Medium	Medium	Medium	Medium	Medium	Low

Figure D-8a. Remedial approach targeting pump and treat (uncemented sandstone impacted by an early- to midterm release of PCE DNAPL).

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Medium	Medium	Low	Medium	Medium	Low
NAPL	Medium	High	Medium	NA	NA	NA
Dissolved	Medium	Medium	Low	Medium	Medium	Low
Sorbed	Medium	Medium	Low	Medium	Medium	Low

Figure D-8b. Remedial approach targeting ISCO with short lasting reagent (uncemented sandstone impacted by an early- to midterm release of PCE DNAPL).

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Medium	Medium	Low	Medium	Medium	Low
NAPL	Medium	High	Medium	NA	NA	NA
Dissolved	Medium	Medium	Low	Medium	Medium	Low
Sorbed	Medium	Medium	Low	Medium	Medium	Low

Figure D-8c. Remedial approach targeting ISCO with longer lasting reagent (uncemented sandstone impacted by an early- to midterm release of PCE DNAPL).

	Low or Non Transmissive	Transmissive		Transmissive		Low or Non Transmissive
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	Low	Low	Medium	Medium	Low
NAPL	Low	Low	Low	NA	NA	NA
Dissolved	Low	Low	Low	Medium	Medium	Low
Sorbed	Low	Low	Low	Medium	Medium	Low

Figure D-8d. Remedial approach targeting thermal remediation.

	Low or Non Transmissive	Transmissive		Transmissive		Low or Non Transmissive
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	Low	Low	Medium	Medium	Low
NAPL	Low	Low	Low	NA	NA	NA
Dissolved	Low	Low	Low	Medium	Medium	Low
Sorbed	Low	Low	Low	Medium	Medium	Low

Acronyms

1,1,1-TCA	1,1,1-trichloroethane
1,1-DCE	1,1, dichloroethene
2D, 3D	two dimensional, three dimensional
AC	activated carbon
ATP	Adenosine triphosphate
AFB	Air Force Base
AFCEC	Air Force Civil Engineer Center (formerly AFCEE)
AFCEE	Air Force Center for Engineering and the Environment (changed to AFCEC)
cc	cubic centimeter
cDCE	cis-1,2-dichloroethene
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (SuperFund)
CF	chloroform
CFR	Code of Federal Regulations
***cis*-1,2-DCE or *cis*-DCE**	*cis*-1,2-dichloroethylene
Cl	Chlorine
CO_2	Carbon dioxide
COC	contaminant of concern
COD	chemical oxygen demand
COPC	contaminant of potential concern
CPT	cone penetrometer testing
CSM	conceptual site model
CT	carbon tetrachloride
Cu	Copper
CVOC	chlorinated volatile organic compound
CWA	Clean Water Act
DBMS	data base management system
DCA	Dichloroethane
DCE	dichloroethene
DDD	dichlorodiphenyldichloroethane
DDE	dichlorodiphenyltrichloroethylene
DDT	dichlorodiphenyltrichloroethane
DDX	dimethyl dioxane
DEC	Department of Conservation

DEP	Department of Environmental Protection
DGM	digital geophysical mapping
DIC	Dissolved inorganic carbon
DL	detection level
DNAPL	dense nonaqueous phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	Department of Transportation
DPT	direct-push technology
DQO	data quality objective
DQOs	data quality objectives
ECOS	Environmental Council of the States
EDB	1,2-dibromoethane
Eh	oxidation-reduction potential
EMD	Environmental molecular diagnostics
EMI	electromagnetic induction
EPA	Environmental Protection Agency
ERH	Electrical resistance heating
ERIS	Environmental Research Institute of the States
ESTCP	Environmental Security Technology Certification Program
FID	flame ionization detector
$\mathbf{F_{oc}}$	fraction of organic carbon
g	Gram
GAC	granular activated carbon
GC	gas chromatography/chromatograph
GC/ECD	Gas chromatograph/electron capture detector
GC/MS	gas chromatography/mass spectrometry
GIS	geographic information systems
GPS	Global Positioning System
GW	groundwater
GWSDAT	Groundwater Spatiotemporal Data Analysis Tool
H	Hydrogen
Hg	mercury
HPT	hydraulic profiling tool
IBT	internet-based training
IC	institutional control
IDSS	integrated DNAPL site strategy

ISB	in situ bioremediation
ISC	integrated site characterization
ISCO	in situ chemical oxidation
ISCR	in situ chemical reduction
ITRC	Interstate Technology and Regulatory Council
KDHE	Kansas Department of Health and Environment
L	Liter
LiDAR	Light Detection and Ranging
LIF	laser induced fluorescence
LLDPE	linear low density polyethylene
LNAPL	Light nonaqueous phase liquid
M	molar
MassDEP	Massachusetts Department of Environmental Protection
MDEQ	Michigan Department of Environmental Quality
MDEQ	Montana Department of Environmental Quality
mg	Milligrams
MGP	manufactured gas plant
MiHpt	membrane interface probe hydraulic profiling tool
MIP	membrane interface probe
mL	Milliliter
MLE	multiple lines of evidence
MNA	monitored natural attenuation
MNR	monitored natural recovery
Mo	Molybdenum
MS	mass spectrometry
MW	monitoring well
N	Nitrogen
NAPL	nonaqueous phase liquid
NASA	National Aeronautics and Space Administration
NAVFAC	Naval Facilities Engineering Command
ND	nondetect
NFA	no further action
NJDEP	New Jersey Department of Environmental Protection
NMR	nuclear magnetic resonance
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NYSDEC	New York State Department of Environmental Conservation
O	Oxygen
O&M	operation and maintenance
OC	organic carbon

OM&M	operation, maintenance and monitoring
ORP	oxidation reduction potential
OSHA	Occupational Safety and Health Administration
OSWER	USEPA Office of Solid Waste and Emergency Response
OTV	Overlay Transport Visualization
OU	operable unit
OVA	organic vapor analyzer
PAH	Polycyclic aromatic hydrocarbon
PAH	petroleum halogenated hydrocarbon
Pb	Lead
PCBs	Polychlorinated biphenyls
PCE	perchloroethene (tetrachloroethylene)
PCP	pentachlorophenol
PDB	polyethylene diffusion bag
PDBS	passive diffusion bag samplers
PID	photoionization detector
PIG	pipeline inspection gauge
PITT	partitioning Interwell tracer test
POC	point of compliance
Q	quantitative
QA	quality assurance
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
QC	quality control
QL	qualitative
RAO	remedial action objective
RBCA	risk-based corrective action
RCRA	Resource Conservation and Recovery Act
RI	Remedial Investigation
RI/FS	remedial investigation/feasibility study
ROD	record of decision
ROI	return on investigation
RP	responsible party
S	Sulfur
SAP	sampling and analysis plan
SDWA	Safe Drinking Water Act
SG	specific gravity
SIM	selective ion monitoring
SIMS	Secondary-ion mass spectrometry
SIP	stable isotope probe

SMART	specific, measureable, attainable, relevant, time-bound (referring to goals)
SPI	sediment profiling imaging
SQ	Semiquantitative
SRB	sulfate-reducing bacteria
SVE	soil vapor extraction
SVOC	semivolatile organic compound
TBA	tert-butyl alcohol, an oxygenate
TBEE	tert-butyl-ethyl ether, an oxygenate
TBT	tributyltin
TCA	trichloroethane
TCD	thermal conductivity detector
TCE	trichloroethylene
TCE	trichloroethene
***tceA* gene**	trichloroethene reductive dehalogenase
TCFE	Trichlorofluoroethylene
TCH	Thermal conductance heating
TCLP	Toxicity Characteristic Leaching Procedure
TMB	trimethylbenzene
TMO	Toluene monooxygenase
TNT	2,4,6-trinitrotoluene
TOC	total organic carbon
TOD	Toluene 2,3-dixoygenase
TPH	total petroleum hydrocarbons
TSCA	Toxic Substances Control Act
TSS	total suspended solids
TVOC	total volatile organic compounds
ug	Micrograms
USDOE	U.S. Department of Energy
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UST	underground storage tank
VC	Vinyl Chloride
vcrA	Vinyl chloride reductase (varietal A), a reductive dehalogenase gene
VFAs	Volatile Fatty Acids
VI	vapor intrusion
VOC	volatile organic compound
Zn	Zinc
ZVI	zero-valent iron
$\mu g/m^3$	microgram per cubic meter

Glossary

A

advection
Transport of solutes by flowing groundwater.

anastomosing
Connection of two normally divergent structures.

anisotropy
The condition under which hydraulic conditions of an aquifer (usually hydraulic conductivity) show variations with the direction of measurement in a geologic formation.

aperture
The perpendicular distance in a fracture between adjacent rock walls.

azeotrope
A mixture of two liquids that has a constant boiling point and composition throughout distillation.

asperity
A localized point of contact along a fracture surface.

C

capillary force
The force of molecular attraction between geologic materials and water in the unsaturated zone which draws water upward.

cleavage (mineral, rock)
The tendency of a mineral to break along planes determined by the crystal lattice; also, the tendency of a bedded rock to split along definite, parallel, closely spaced planes.

connectivity (fracture)
The greater the fracture density, the greater the fracture length, the greater the potential for fractures to be connected.

CSM
Conceptual Site Model.

D

Darcy's Law
An empirical equation that defines volumetric discharge through a permeable medium.

diffusion
The process of ionic or molecular constituents moving in the direction of a concentration gradient.

dispersion
The spreading of dissolved substances due to the combined effects of mechanical mixing and diffusion.

dissolution
The process of dissolving.

dual porosity

Rock with two distinctly porosity one in the rock matrix and one in the fractures of the rock.

E

equivalent porous medium

A fractured bedrock system which is treated as a homogeneous porous medium for the purposes of conceptual, analytical and numerical modeling.

F

fractured rock CSM

A representation of a fractured rock hydrogeologic system, which describes and explains key characteristics of groundwater flow, and contaminant transport and storage, in the rock matrix and fractures (including all types of partings and openings).

fabric

When applied to rocks, includes the complete spatial and geometrical configuration of all those components that make up the rock. It covers terms such as texture, structure and preferred orientation and so is an all-encompassing term that describes the shapes and characters of individual parts of a rock mass and the manner in which the parts are distributed and oriented in space. The individual parts are only considered as contributing to a fabric if they occur repeatedly in a reproducible manner form one sample of rock to another. (Hobbs B. E. 1976)

H

heteroazeotrope

An azeotrope where the vapor phase coexists with two liquid phases.

hydraulic conductivity (K)/permeability

The rate that water can move through a saturated porous medium; defined as a proportionality constant (which includes the intrinsic permeability, the fluid density, a gravitational constant and the dynamic viscosity).

I

infilling (fracture)

Debris, weathering products, cementation or biofilm in a fracture or on the fracture wall will affect flow.

intrinsic permeability

The property of geologic material to transmit fluid (not the same as “permeability”).

J

joint

A fracture or break in rock that lacks any visible or measurable movement parallel to fracture surface.

L

laminar flow

Fluid flow which is smooth, straight and parallel to the channel walls.

length (fracture)

The longer the fracture, the further unimpeded flow is likely to occur and the more likely fractures will interconnect.

M

macroscopic flow

Flow occurring at the regional to individual parcel scale, including features that range from approximately 30 meters to tens of kilometers in length.

mesoscopic

Flow occurring at the sitewide scale, or between sites; features are observable in individual boreholes and between boreholes.

microfracture

A bedrock fracture having an aperture of less than one millimeter.

microjoint
A microfracture with no measurable movement parallel to the surface.

microscopic
A scale of features not discernible to the naked eye.

O

orientation
The strike and dip of an inclined plane.

P

permeability
Intrinsic measure of a porous material to allow fluids to past through it.

planarity
Open flat fractures provide unimpeded flow while wavy fractures may lock open, or may form dead ends where fracture surfaces touch.

plume
An elongated body of groundwater containing contaminants, emanating from a point source and migrating within a hydrogeologic unit(s). The shape and movement of the mass of the contaminated water is affected by the geology, bio/geo chemistry, contaminant(s), and the flow characteristics of the groundwater. Because they often travel through discrete fractures and fracture sets, bedrock plumes are commonly asymmetrical in shape. Therefore, in bedrock, it may be more appropriate to use the terms "contaminant distribution" or "area of impact".

porosity (primary, secondary)
The ratio of the void volume to the total volume in geologic material. For primary porosity the void volume is the intergranular or intercrystalline space. For fracture porosity the void volume is the space within fractures.

precipitation
The process of chemical deposit formation from a solution.

R

roughness
A smoother fracture surface results in less frictional resistance to flow and fewer surfaces for solids or microbes to attach to.

S

significant data gap
Missing or incomplete information, which limits the formulation of a scientifically defensible interpretation of environmental conditions and/or potential risks in a bedrock hydrogeologic system. Significant Data Gaps are likely to exist if more than one Bedrock CSM can be supported by the data.
(http://www.ct.gov/deep/lib/deep/site_clean_up/guidance/Site_Characterization/Final_SCGD.pdf)

solution channel
Tubular or planar channel formed by solution in carbonate-rock terrains, usually along joints and bedding planes.

T

terrane
A fault bounded area or region with a distinctive stratigraphy, structure, and geologic history.

transmissivity (T)
The product of hydraulic conductivity and aquifer saturated thickness. For a discrete fracture the aquifer saturated thickness is the effective aperture.

turbulent Flow
: Fluid flow along irregular paths.

V

vuggy
: Small Cavity in a rock or vein, usually lined with crystals.

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