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
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> *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).

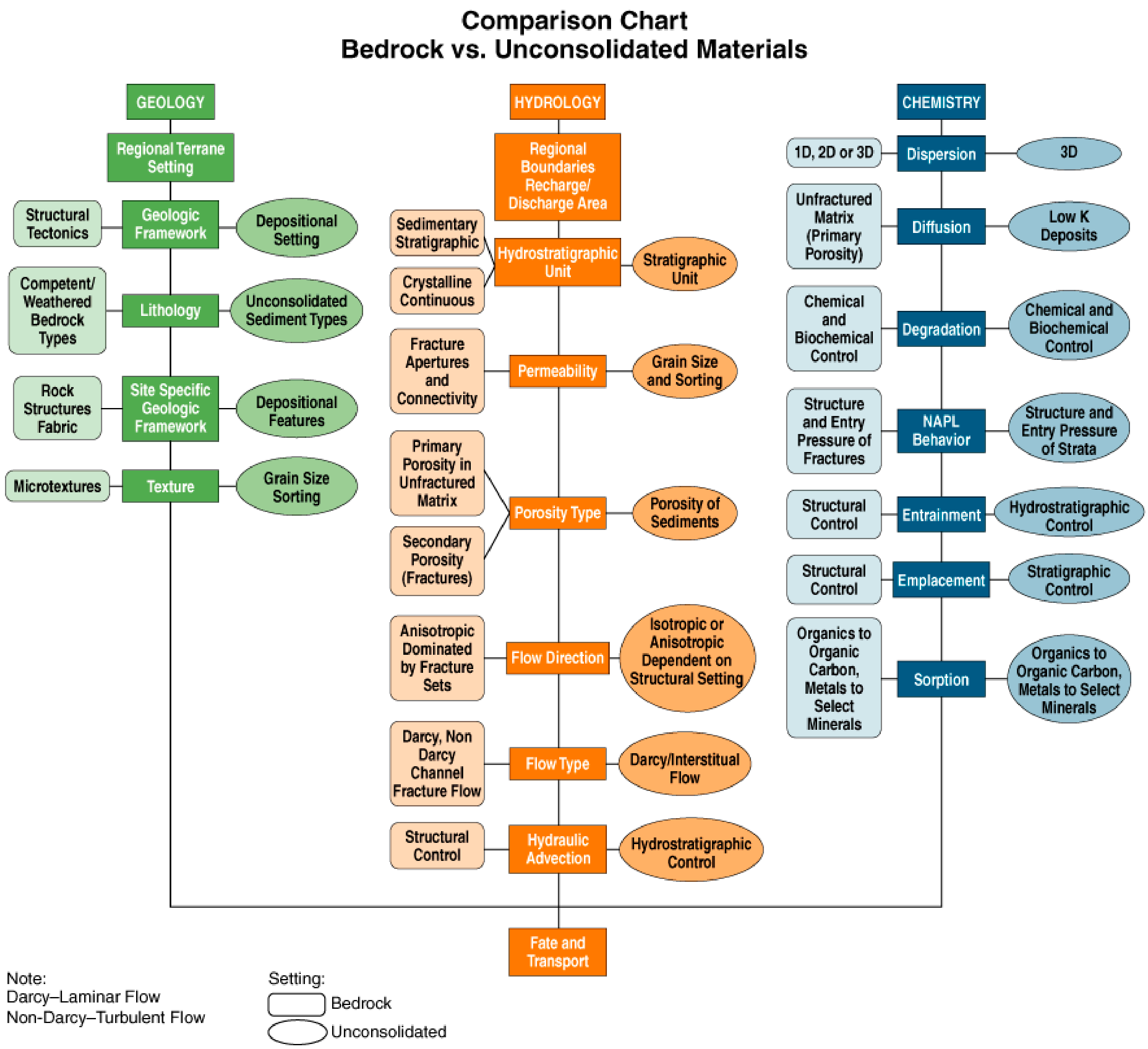

Figure 1-1. Bedrock versus unconsolidated rock types.

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.