APPENDIX A

1. The Discrete Fracture Network (DFN) Approach for Contaminated Bedrock Site Characterization

Beth L. Parker and John A. Cherry

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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A comprehensive methodology known as the Discrete Fracture Network (DFN) Approach has been developed since the mid-1990's as a framework for characterization of contaminated sites on fractured rock. This article provides an overview of the Approach and is followed by eight additional articles that describe the various methods that constitute this Approach. The ninth article also describes the general nature of contaminated sites on fractured sedimentary bedrock where the Approach is being comprehensively applied. The goal of this Approach, developed by a research team led by Dr. Beth Parker at the University of Guelph, Canada, is appropriate data acquisition followed by evaluation of the data for the improved understanding needed for science-based decision making for site characterization, risk assessment, and remediation. This field approach was developed to take advantage of the capability of powerful numerical models developed earlier in the 1980's-1990's for simulation of groundwater flow and contaminant transport and fate in rock with fracture networks and porous, permeable rock matrix blocks between fractures. These models had not been used to represent real-site conditions due to the lack of suitable field data (i.e., lack of measured input parameter values). The field information and the DFN numerical models are used to advance site conceptual models (SCMs) that are the essential basis for contaminated site decision-making.

This Approach is based on the premise that the characterization of contaminated sites and SCM development should be separate from and a prerequisite to long-term monitoring. In the DFN Approach, either an initial SCM or multiple SCMs (e.g., multiple hypotheses) guide data collection for the site. As application of the Approach progresses, the number of hypotheses is reduced and the SCM is advanced in an iterative manner, as key questions are addressed to an appropriate degree of refinement and reliability.

The DFN Approach for contaminated bedrock is based on the recognition that contaminant mass occurs in both the fractures and the porous blocks of rock existing between the fractures. Most contaminant mass commonly resides in the rock matrix, due to molecular diffusion and sorption, but most groundwater flow, and hence contaminant transport, occurs in the fractures. Therefore, emphasis in this Approach is directed at acquisition of data from both the fractures and the rock matrix. To date, the DFN Approach has only been comprehensively applied to sites on sedimentary bedrock where the rock matrix has porosity in the range of 4-20%, such that diffusion in the matrix is a strong process influencing contaminant behaviour.

The chart in Figure 1 summarizes the many components of the DFN Approach. Continuous rock core obtained by diamond bit drilling is the key component, because this is used as the primary means of determining the contaminant distribution. The rock core contaminant analyses are done on small pieces of rock collected at 1 ft spacing on average along the core, which is typically drilled to 250 ft or deeper. This method represents high resolution determination of the contaminant distributions. From the starting point of rock core contaminant measurements (i.e., detailed profiles) first applied in 1997, many other high resolution field methods have been added. Each component shown in Figure 1 is a high resolution data acquisition method for improved site characterization that has recently become available.

The left side of Figure 1 displays the components pertaining to observations and measurements made using the rock core; the right side shows the types of measurements obtained from the borehole. Two elements of the DFN Approach clearly distinguish it from conventional approaches to bedrock contaminated site characterization: (1) the use of the rock core for contaminant analyses at a fine scale (Article 2) (i.e., analyses of chemicals in small pieces of the rock core selected at small spacing along the core) and (2) use of flexible-impervious liners first to seal holes to prevent cross-connection, second to measure transmissivity profiles, and third to allow high resolution temperature measurements inside the water column of the lined hole to identify hydraulically active fractures without the masking effects of vertical connectivity (Articles 3 and 4).

The borehole is used primarily to collect rock core contaminant data, aimed at development of understanding of the contaminant distribution. In the DFN Approach, emphasis is directed at minimizing the length of time that the hole is left open after completion of drilling. Therefore, although the hole can be used for open-hole geophysical measurements (Article 5), such as geophysical imaging (e.g., acoustic televiewing) and hydraulic tests using straddle packers (Article 6), the time allocated to this open-hole data acquisition is purposefully limited. Furthermore, the DFN Approach avoids using data collected from partially or fully cross-connected open holes as a basis for understanding key features in the natural system.

Immediately after the hole is drilled, a liner is installed in the hole using a procedure that

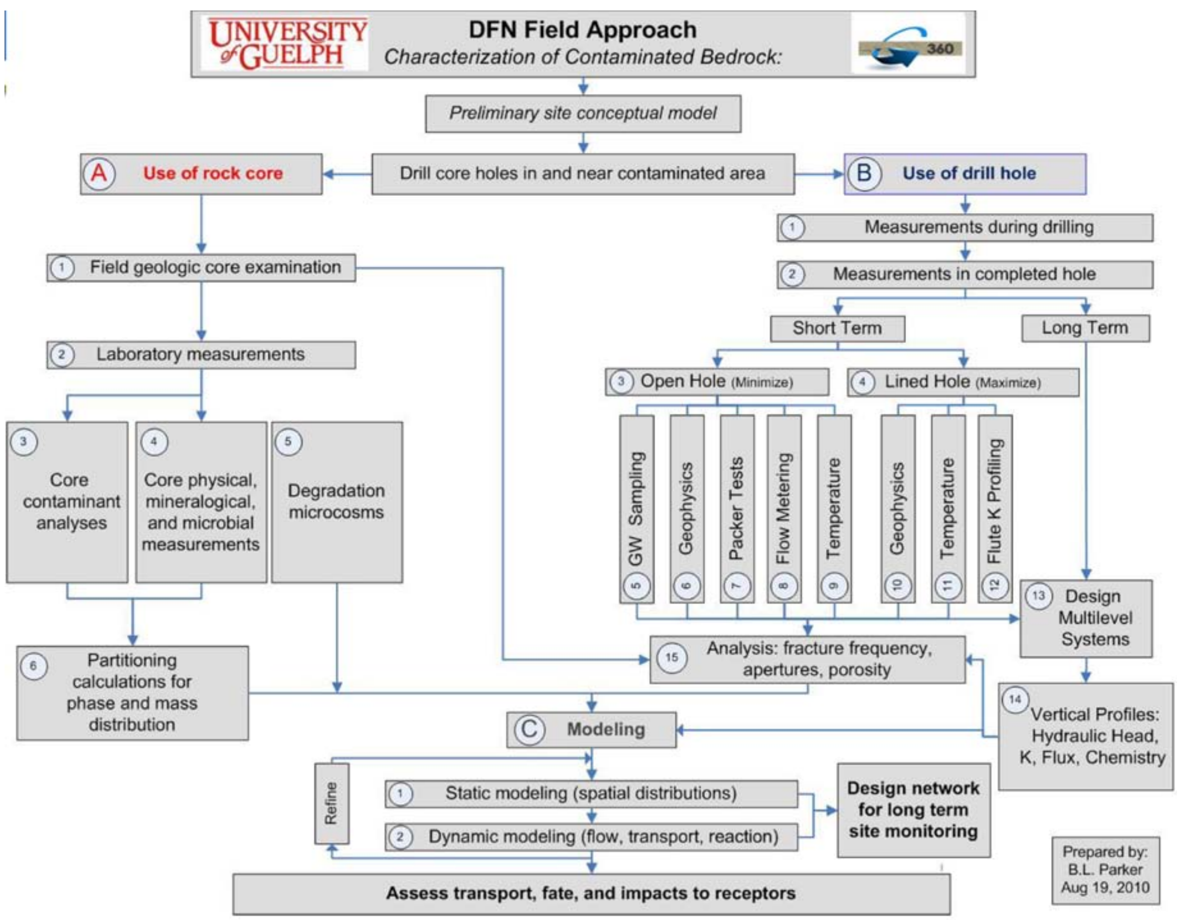

Figure 1. Summary of the components of the Discrete Fracture Network Approach for contaminated bedrock site characterization.

provides a transmissivity profile (Article 3). High resolution passive or active temperature profiling is then done inside the liner (Article 4) as a sensitive tracer of active groundwater flow in sealed (i.e., natural) conditions. The liner is removed for a short period at a later date to allow open-hole geophysical measurements (Article 5) and hydraulic tests (Article 6). Then, after the rock core and borehole data have been compiled and assessed, the liner is removed for the last time so a depth-discrete multilevel system (MLS) (Article 7) or a conventional monitoring well can be installed in the hole, from which data are then acquired. These data are used as part of the site characterization, which includes assessment of various hypotheses and development of a robust SCM. Application of this approach at eight sites has provided a general conceptual model for the nature of contaminant plumes in fractured sedimentary rock (Article 8). After the site characterization is complete, a long-term groundwater monitoring network is established based on the DFN data sets and the SCM. The groundwater system is monitored at the appropriate locations and depths over long periods of time and provides sentry monitoring relevant to potential contaminant receptors.

In the DFN Approach, emphasis is directed at determining all of the fractures in each hole in which groundwater flow occurs under ambient (natural) conditions. Results for the DFN Approach applied at eight contaminated sites on sedimentary bedrock show that contaminant distributions can be explained if and only if groundwater flow and contaminant transport occur in a multitude of interconnected fractures (Article 8). Therefore, improved sensitivity for identifying hydraulic activity under natural conditions using both contaminants (which at most contaminated sites have been present for decades) and temperature as tracers, as well as better quantification of fractures and fracture networks geometry, are key themes in the DFN Approach.

The development of the DFN Approach began in 1996 and was initially applied to a site in California with interbedded, fractured sandstone and shale. The DFN Approach is now well established in the USA and Canada at eight sites in sedimentary bedrock (e.g., sandstone, dolostone, and shale) where chlorinated volatile organic compounds (mostly tricholoroethylene; TCE) are the primary contaminants of concern. Although several components of the DFN Approach methodology continue to be improved and refined, the results obtained to date from these eight field sites provide a science-based framework for decision making regarding the transport and fate of contaminants, remediation, and long-term monitoring. The nine articles describing the DFN Approach and included in this series are listed below.

1. The Discrete Fracture Network (DFN) Approach for Contaminated Bedrock Site Characterization
2. Rock Core Analyses to Determine Contaminant Mass and Phase Distributions in Fractured Rock
3. Impermeable Flexible Liners (FLUTe™) for Sealing Boreholes and Obtaining Depth-Discrete Measurements of Permeability and Flow in Fractured Bedrock
4. High Resolution Temperature Profiling in Sealed Boreholes for Identifying Hydraulically Active Fractures
5. Role of Borehole Geophysics in the DFN Approach for Contaminated Fractured Rock Sites
6. Improved Methodology for Straddle-Packer Hydraulic Testing in Fractured Rock
7. Design Strategies for High-Resolution Multilevel Monitoring Systems for Fractured Rock Sites
8. Nature of Organic Solvent Source Zones and Plumes in Fractured Sedimentary Rock
9. Static and Dynamic Modelling Based on DFN Characterization at Contaminated Bedrock Sites

Associated Publications

Parker, B.L. 2007. Investigating contaminated sites on fractured rock using the DFN Approach. *In:* Proceedings of the U.S. EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation, September 24-26, 2007, Portland, Maine.

2. Rock Core Analyses to Determine Contaminant Mass and Phase Distributions in Fractured Rock

Beth L. Parker

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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There are many contaminated sites in fractured rock where the nature and extent of the contamination must be determined. A comprehensive approach is now available to facilitate the understanding and prediction of contaminant behaviour in fractured bedrock involving a suite of field and laboratory methods and models. These methods, known collectively as the Discrete Fracture Network (DFN) Approach (Article 1 in this series), have been developed by a multidisciplinary research team led by Beth Parker at the University of Guelph. This article describes an essential method within the DFN Approach: the analysis of rock core samples for contaminant, geochemical, physical, and microbial characteristics. Typically, the majority of groundwater flow in bedrock occurs through networks of interconnected fractures between blocks of low permeability rock containing relatively immobile porewater. In areas of known or suspected contamination where the rock has appreciable porosity (e.g., >1%), the first step in the application of the DFN Approach is to drill continuously cored holes and take numerous, closely spaced discrete samples from the core for laboratory analysis of contaminant concentration. Contaminants occur in the rock matrix between fractures as a result of contaminants diffusing from the fractures into the matrix over years or decades. Diffusion out of the rock matrix back into fractures now occurs in some zones at older contaminated sites.

Although nearly all groundwater flow occurs in the interconnected fractures, rock core contaminant analysis from our studies at numerous sites shows that nearly all contaminant mass occurs in the low permeability rock matrix (Figure 1). Although drilling does not disturb the contamination in the matrix, we need to be mindful of the extent of dense non-aqueous phase liquid (DNAPL) dissolution and incorporate it into our drilling plans to prevent possible cross-connection/downward mobilization. Some sites in sedimentary rock have evolved to the non-DNAPL conditions shown in Figure 2c; downward mobilization of DNAPL is no longer an issue at these sites. Figure 3a conceptually illustrates the rock core sampling approach and correlations between fracture location and matrix concentrations of contaminants.

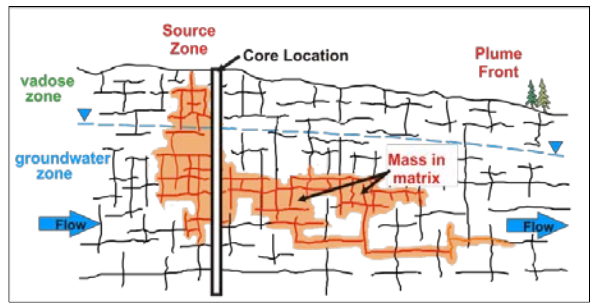

Figure 1. Conceptualization of contaminant migration and matrix diffusion in a fractured sedimentary rock environment.

Figure 3b provides example results from a fractured sandstone site in California where trichloroethylene (TCE) and degradation products are the primary contaminants. At this site and many others in North America, rock core analysis rather than monitoring wells has been used to determine contamination nature and extent. The rock core chemical analyses produce total contaminant mass in the sample and these results are converted by a calculation procedure into the dissolved and sorbed fractions of the total mass. Figure 3b displays the dissolved concentrations and solubility of TCE. None of the rock core concentrations are above or even close to TCE solubility in water. Therefore, these results indicate that, for this hole, TCE DNAPL is no longer present but the rock matrix contains abundant mass.

Monitoring wells or multilevel monitoring systems are much less effective for site characterization because of complications due to cross-contamination between different levels in each hole. These devices, although useful for other purposes, do not determine contamination in the rock matrix. In this example (Figure 3b) contaminant concentrations were measured at spacing of 0.3 to 1 ft. This spacing is appropriate given contaminant type, age, and fracture characteristics. This spacing is typical for sedimentary rock, such as sandstone, limestone, dolostone and shale, where the primary contaminants have minimal sorption. At sites where contaminant diffusion into the rock matrix is slower, due to lower rock porosity or more sorption, sample spacing is smaller and concentrated around fractures. Each contaminant category (e.g., volatiles, semi-volatiles, non-volatiles, organics, metals) requires specific procedures for sampling, sample preservation, processing, and analysis.

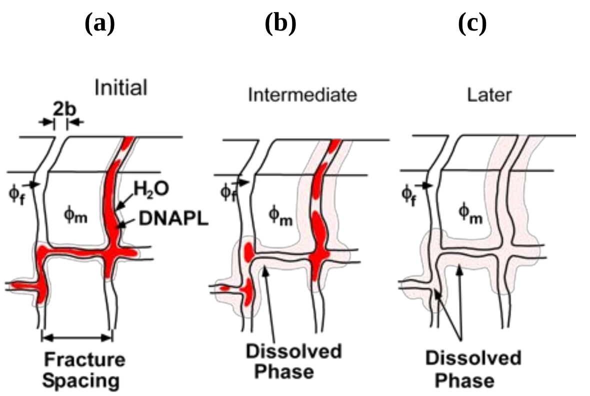

Figure 2. Conceptual model of DNAPL distribution in fractured porous rock. (a) Initial conditions with the DNAPL invading the fracture, followed by dissolution and subsequent diffusion into the porous matrix. (b) Intermediate time conditions, with disconnected DNAPL blobs due to loss by diffusion into the matrix. (c) Later time conditions when all DNAPL has dissolved and diffusion haloes exist around previously DNAPL-filled fractures.

The first application of methods to produce detailed profiles of organic contaminant distributions in sedimentary rock core was done beginning in 1997 at a sandstone site in California and independent of but at the same time as the British Geological Survey for sites on chalk and sandstone in the U.K. Modifications to field procedures and laboratory analytical methods have improved both detection limits and the efficiency of sample processing and analysis. Cores are also used for other measurements, such as porosity, permeability, and mineralogy (e.g., solid-phase organic content). The contaminants in the mobile fracture water can cause contaminant plumes to expand beyond source zones; however, the contaminant mass diffused into the relatively immobile matrix water is the most difficult to remove by engineered remediation. To understand the contaminant distribution and implement effective, long-term monitoring and, ultimately, effective remediation strategies, the occurrence of contamination in both the rock matrix and the fractures must be taken into account. The DFN Approach facilitates this through utilization of the open borehole after core drilling and extraction to conduct various types of tests, such as flexible liner hydraulic K profiling, geophysical logging, hydraulic testing, and use of multilevel monitoring systems to characterize fracture flow. However, the rock core contaminant results guide these other measurements in the DFN Approach.

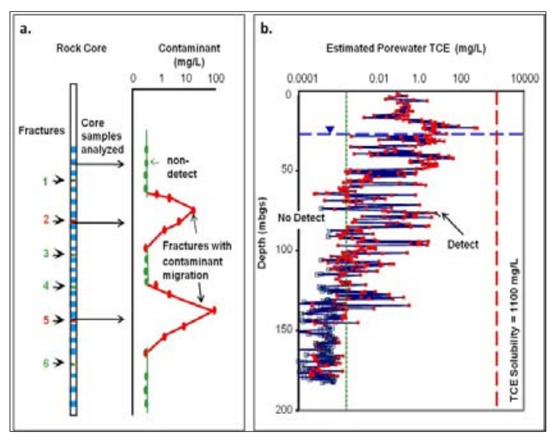

Figure 3. (a) Rock core sampling approach and conceptual profile showing contaminant mass in the matrix. (b) Rock core results for TCE at a fractured sandstone site in California.

Associated Publications

Kennel, J.R. 2008. Advances in Rock Core VOC Analyses for High Resolution Characterization of Chlorinated Solvent Contamination in a Dolostone Aquifer. Master's thesis, Department of Earth & Environmental Sciences, University of Waterloo, Waterloo, ON.

Sterling, S.N. 1999. Comparison of Discrete Depth Sampling Using Rock Core and a Removable Multilevel System in a TCE Contaminated Fractured Sandstone. Master's thesis, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON.

Sterling, S.N., B.L. Parker, J.A. Cherry, J.H. Williams, J.W. Lane Jr., and F.P. Haeni. 2005. Vertical cross contamination of trichloroethylene in a borehole in fractured sandstone. *Ground Water* 43, no.4: 557-573.

3. Impermeable Flexible Liners (FLUTe™) in Fractured Bedrock for Sealing Boreholes and Obtaining Depth Discrete Measurements of Permeability and Flow

John A. Cherry[1], Beth L. Parker[1], and Carl Keller[2]

Center for Applied Groundwater Research[1]
University of Guelph
Guelph, ON N1G 2W1

Flexible Liner Underground Technologies[2]
FLUTe™
Santa Fe, NM 87506

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Intensive investigations of contaminated sites in fractured rock are increasing in North America, with application of many new field methods. A multidisciplinary research team at the University of Guelph (UofG), led by Dr. Beth Parker, has developed a comprehensive approach for such investigations aimed at delineation of contaminant distributions and understanding the transport and fate of contaminants in both fracture networks and the rock matrix blocks between the fractures. This is known as the Discrete Fracture Network (DFN) Approach, as described in Article 1 of this series. This approach includes important new methods, several of which involve "flexible liners", referred to as FLUTe™ technologies, invented and developed by Carl Keller, founder of Flexible Liner Underground Technologies Ltd., Santa Fe, New Mexico. This article focuses on the liner components of the DFN Approach. Collaborations between the UofG team and FLUTe have been on-going since 1997 to demonstrate, test, and extend the unique capabilities of these technologies for investigations in boreholes through fractured rock.

A "liner" is an impervious cylindrical sleeve installed in boreholes by inversion with water, such that the sleeve "lines" the hole to form a tight seal. This liner serves as a continuous inflated packer, preventing hydraulic cross-connection in the hole caused by water flowing into the hole from some fractures and then moving up or down to exit the hole from other fractures. In areas where groundwater contamination exists in the bedrock, this cross-connecting flow causes chemical cross-contamination that confuses chemical data interpretation and commonly makes the contamination worse. Therefore, in some jurisdictions of North America (e.g., New Jersey) regulations for contaminated site investigations now require that soon after a hole is drilled, it must be temporarily sealed, immediately have a monitoring system installed, or immediately and permanently be sealed with grout. The FLUTe liner is the only practical method now available to quickly but temporarily seal a hole.

In addition to accomplishing the goal of sealing the hole, these liners are used to acquire data from the hole prior to installation of a well or a multilevel monitoring system, such as the Westbay® system, Waterloo system, or a Water FLUTe™ system (described in Article 7). Prior to 2005, FLUTe liners were installed in hole solely to seal the hole against cross-contamination. However, two other major advantages derived from the liner installation have since been developed: measurement of the borehole hydraulic conductivity as the liner is installed (K profiling) and high resolution temperature measurement in the static water column inside the liner (described in Article 4). Figure 1 provides an explanation of the K-profiling method and gives an example profile. This involves monitoring the rate of descent, or velocity, of the inflating liner going down the hole. The liner velocity profile (Figure 1) is used to calculate values for the transmissivity (T) and hydraulic conductivity (K) of permeable zones, which are then plotted in profile. Photographs of the installation and removal of a liner are shown in Figure 2. The results from the FLUTe K profiling are used to select and prioritize intervals for high resolution straddle packer hydraulic testing (described in Article 6). Thus, liner profiling and hydraulic tests using straddle packers are used in a synergistic manner.

(a) (b)

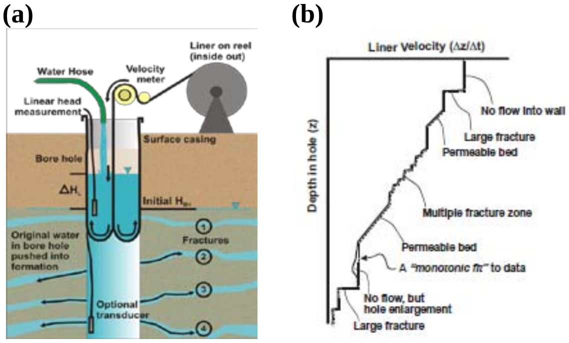

Figure 1. (a) Illustration of the system components for the profiling method. The system controls and measures parameters relevant to the determination of the fracture location and calculation of discrete fracture flow rates. (b) Hypothetical liner descent velocity profile showing changes caused by several types of borehole features. This profile assumes perfect functioning of the field measurement equipment (i.e., no noise).

A new temperature profiling probe developed by Peeter Pehme, a UofG team member, can be applied inside the liner to identify hydraulically active fractures. This method typically shows many more active fractures than temperature profiles with no liner in the hole (Article 4). With no liner in the hole, the thermal evidence for most of the active fractures is obliterated by borehole cross-connection effects. Therefore, the liner provides the means for greatly enhancing the sensitivity for fracture identification. Some types of geophysical logging can also be done inside the lined hole to obtain information about the geology. FLUTe liners are temporary; after the K and temperature profiling are done and interpretation of all borehole data is complete, the liner is removed for installation of a multilevel system or monitoring well, which are designed based on the interpreted data. The manner by which the FLUTe liner goes down the borehole makes it uniquely suitable for delivering various types of monitoring devices to many different depths in each hole, such as groundwater sampling pumps, pressure transducers, and other types of measurement devices currently being developed. After sufficient data have been obtained, these monitoring systems can be removed by pumping the water out of the interior of the liner system. This allows the hole to be easily decommissioned or used for other purposes. The FLUTe-based methods described above are being applied intensively by the UofG team and collaborators in the research context at eight contaminated bedrock sites in Canada and the United States. The methods are also being used in a non-research context at many other sites across North America and beyond. Although these methods are now serving the needs of the professional site-investigation community, as for all developing technologies understanding the site circumstances where each technology is best suited is necessary, as are refinements to the process to address extreme or unusual borehole conditions. This is now the focus of much of the UofG collaboration with FLUTe.

(a) (b)

Figure 2. (a) Photograph of liner installation. The liner comes off the reel (background) and is fed through a velocity meter (foreground) as it descends down the hole due to the force of the driving head (ΔH) created by adding water into the liner. (b) Photograph of liner removal using a specifically designed "capstand" system, which prevents the liner from tearing during removal.

Associated Publications

Cherry, J.A., B.L. Parker, and C. Keller. 2007. A new depth-discrete multilevel monitoring approach for fractured rock. *Ground Water Monitoring & Remediation* 27, no.2: 57-70.

Keller, C.K., J.A. Cherry, and B.L. Parker. 2011. New method for continuous hydraulic conductivity profiling in fractured rock. Submitted to *Ground Water*.

4. High Resolution Temperature Profiling in Sealed Boreholes for Identifying Hydraulically Active Fractures

Peeter E. Pehme and Beth L. Parker

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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This article, the fourth in the Discrete Fracture Network (DFN) Approach for investigating contaminated sites in bedrock series, focuses on a new borehole measurement method to identify fractures showing active groundwater flow under ambient flow conditions. In the DFN Approach, contaminant distribution is primarily determined by rock core analysis described in the second article in this series, and many methods are applied in the cored hole to provide understanding of mechanisms and processes influencing the distribution of groundwater flow in fractures and, in some cases, the matrix. High resolution temperature profiles are measured in the static water column inside the borehole sealed with a flexible fabric impervious (FLUTe™) liner (i.e., passive profiles). This method of preventing cross-connection in boreholes is described in the third article of the DFN series. Once the disturbance of the groundwater system caused by drilling and the open hole dissipates, the temperature profile in the lined hole shows fractures with active groundwater flow without the influence of the borehole (i.e., 'natural' flow conditions). In these active fractures intersecting the borehole, groundwater flows around the liner and imparts its temperature to the static water column inside the liner as measured by the probe. The probe resolves temperature variations to better than 0.002°C. Typically, temperature profiling in lined holes identifies many more hydraulically active fractures than in holes profiled without the liner, as shown in Figure 1.

In this example, two major fractures are detected in the unlined hole profile, but the lined hole profile shows many fractures. In addition, major fractures found in the lined hole are missed entirely by the unlined hole profile. The cross-connection effects in the unlined hole cause the results to misrepresent the ambient groundwater system and thus mislead any assessment of the contaminant behaviour. These passive temperature profiles in the lined holes show the perturbation deep into the rock of transient temperature variations imposed at ground surface from the atmosphere or unseen infrastructure. Therefore, the temperature profiles show the disequilibrium of the thermal regime caused by groundwater heat transport. The passive method of identification of hydraulically active fractures has been enhanced

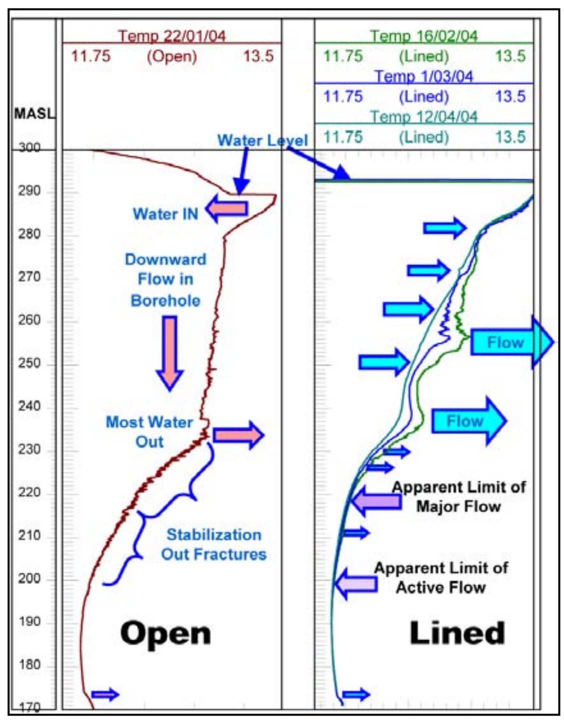

Figure 1. Comparison of basic interpretations of temperature logs collected without heating in open and lined borehole UW1. Blue arrows indicate major and minor flow zones. Red arrows are lower limits of shallow flow based on temperature variability (*Ground Water* [2010], 48, No.2: 191-205).

by use of the Active Line Source (ALS) technique (Figure 2), in which the entire static water column inside the liner is quickly heated for 5-6 hours before the dissipation of the heat is measured by repeated profiling over a few hours. By heating the hole, the sensitivity and depth range for fracture identification is substantially increased.

The goal of applying the DFN field methods is to analyze contaminant transport and fate based on an understanding of processes occurring in both the fracture network, where nearly all groundwater flow occurs, and the rock matrix between fractures. This high resolution temperature profiling method, when used in combination with other DFN methods such as FLUTe hydraulic conductivity profiling, geophysical borehole imaging, and borehole hydraulic tests, provides much of the information needed to apply advanced DFN numerical models (e.g., FRACTRAN, FRACMAN) for the assessment of groundwater flow and contaminant fate and transport as described in previous and later articles in this series. Used in combination, these methods show many more permeable fractures with active flow than detected using conventional methods, and this finding is consistent with the nature of contaminant plumes in fractured rock (Article 9).

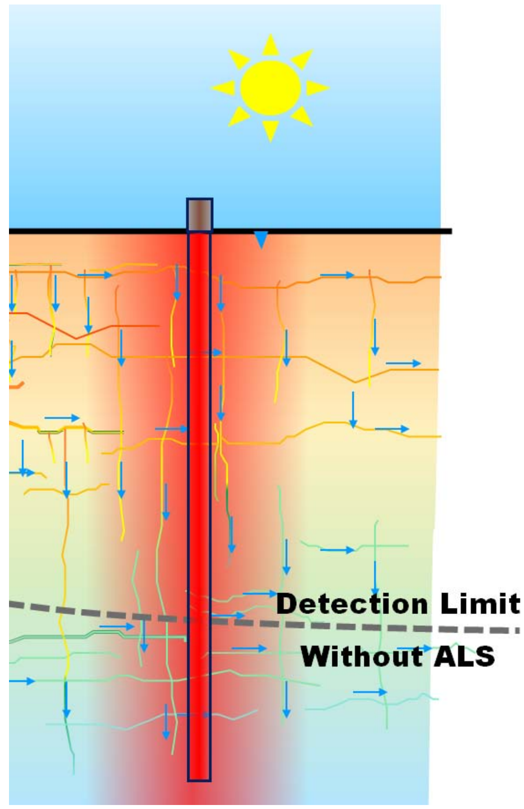

Figure 2. Heating the static water column in a lined hole followed by temperature profiling to observe the heat dissipation (Active Line Source) eliminates the depth limitations of passive temperature logging.

Associated Publications

Pehme, P.E., J.P. Greenhouse, and B.L. Parker. 2007. The active line source (ALS) technique, a method to improve detection of hydraulically active fractures and estimate rock thermal conductivity. *In:* Proceedings of the 60th Canadian Geotechnical Conference and 8th Joint CGS/IAH-CNC Groundwater Conference, 21-24 October 2007, Ottawa, ON, 1-8, Ottawa, Ontario: International Association of Hydrogeologists.

Pehme, P.E., J.P. Greenhouse, and B.L. Parker. 2007. The active line source temperature logging technique and its application in fractured rock hydrogeology. *Journal of Environmental & Engineering Geophysics* 12, no.4: 307-322.

Pehme, P.E., B.L. Parker, J.A. Cherry, and J.P. Greenhouse. 2010. Improved resolution of ambient flow through fractured rock with temperature logs. *Ground Water* 48, no.2: 191-205.

5. Role of Borehole Geophysics in the DFN Approach for Contaminated Fractured Rock Sites

Peeter E. Pehme, Beth L. Parker, and John A. Cherry

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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In the traditional approach to rock site investigations, borehole geophysical methods such as imaging logs and caliper logs are commonly used to identify fractures. However, these methods cannot distinguish between those fractures that have natural flow and those that do not. Nevertheless, borehole geophysics is an important component of the Discrete Fracture Network (DFN) Approach for investigations of contaminated sites on fractured bedrock and is used in combination with other borehole methods to distinguish the hydrological fractures. In the DFN Approach, the emphasis of borehole geophysics is somewhat different than in conventional fractured rock investigations. Some methods are omitted from DFN studies or used only minimally, whereas other techniques are relatively more important. An essential objective in the DFN Approach is the minimization of borehole cross-contamination that occurs when holes are drilled through contamination and the borehole is then allowed to stand open (i.e., with no liner or packers installed to seal the hole). In open holes, chemicals can be transported in the water column from contaminated fractures as a result of head differences in the rock, either up or down the cross-connecting borehole, to other fractures. Borehole cross-connection may cause the nature of the site contamination to worsen and/or result in misleading data interpretation aimed at characterizing the contaminant distribution. In the DFN Approach, flexible, impervious liners (as described in DFN Article 3) are installed soon after the hole is drilled. Borehole geophysical methods requiring open-hole conditions are conducted over a short period of time, either immediately after drilling and borehole development or later when the liner is temporarily removed to allow geophysical logging and hydraulic tests using straddle packers.

Table 1 summarizes the borehole geophysical technologies generally available and indicates the type of insights that each is intended to provide in the context of (i) mineralogy/lithology, (ii) rock matrix porosity and physical properties, (iii) borehole geometric features and fracturing, (iv) groundwater flow, (v) groundwater / fluid chemistry, and (vi) and borehole properties. There is a subtle but important distinction between the properties measured (e.g., an abrupt, narrow change in borehole diameter) and the inferences from that measurement (i.e., a fracture exists) that requires experience to properly assess. Some geophysical tools can be applied in lined holes while others cannot. The diameters of some tools may prevent their use in some boreholes. As for all measurements done in open boreholes through contaminated zones, including packer hydraulic tests, there is a trade-off between the value of the information obtained and the undesirable potential for cross-contamination occurring over the period of time when borehole data collection is being conducted. One of the methods indicated in Table 1, high resolution temperature profiling, is particularly well suited for applications in lined (sealed) holes and is described in more detail in DFN Article 4. Based on our experience applying the DFN Approach at contaminated sites, some geophysical methods that require an open hole, most notably borehole flow metering and full borehole salinity dilution (FEC) logging, should be avoided or minimized in contaminated areas.

Geophysical logging results are used in the DFN Approach in conjunction with other types of borehole information to develop comprehensive interpretations of the hydrogeological conditions at the borehole location, an example of which is shown in Figure 1. Data from the core and the gamma log are used to establish the geological units. The geological log and image logs (acoustic televiewer and video) provide for visual identification of features, including vugs, fractures, fracture zones, and lithology contrasts, but cannot indicate whether these features are capable of or presently transmitting groundwater (i.e., open with flow or connectivity versus closed, sealed fractures). The FLUTe™ liner (see Article 3) transmissivity (T) profile provides evidence of permeable fractures, and the high resolution temperature profile (Flow Interp) identifies fractures for which this method indicates detectable groundwater flow under ambient flow conditions. Borehole geophysics plays an important role in the procedure that produces these values because the image logs, the caliper logs, and the temperature profiles contribute important evidence used to assign the number of permeable fractures (N) to each hydraulic test interval for which transmissivity (T) values have been produced.

The assignment of N to each interval is based on comparing all lines of evidence for what constitutes a permeable fracture. The data sets available depend on the site, mode of contaminant distribution, and circumstances of the investigation. However, gathering as much of this data as practical provides essential inputs for planning multilevel installations, modelling contaminant transport and fate, and formulating a DFN conceptual model to guide the decision making process. The degree to which the various borehole geophysical methods add value in the DFN approach can depend on the site-specific conditions, and the assessment of geophysical methods is an ongoing process. Advanced methods of geophysical logging used in the petroleum industry are now being used in the groundwater field; our experience with these methods is in the early phase and therefore will not elaborate upon them further in this article.

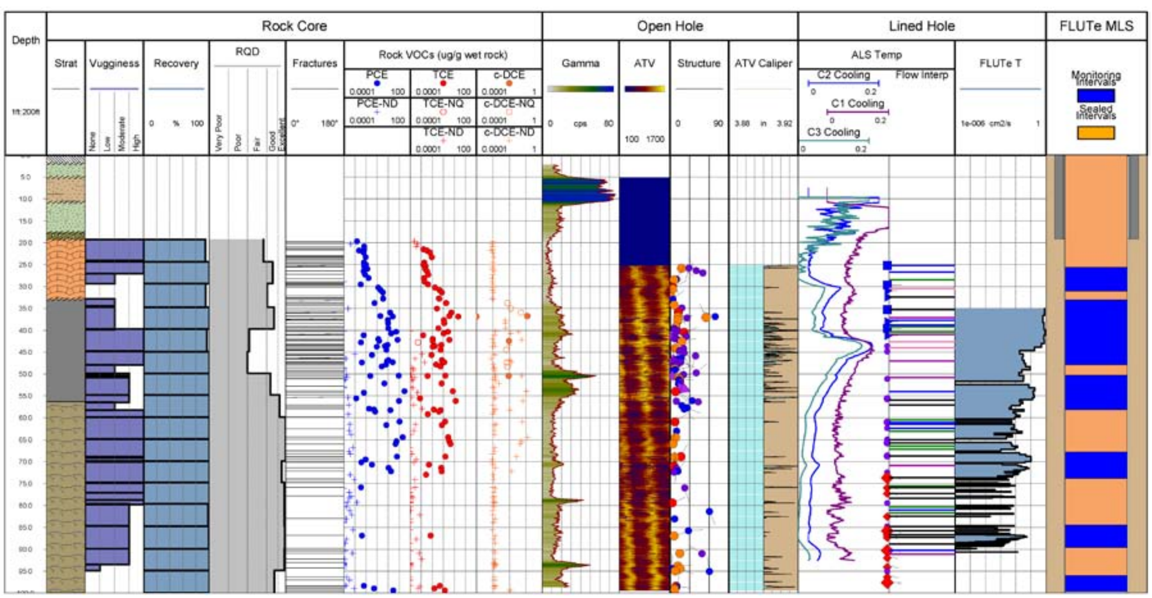

Figure 1. Typical montage of borehole data (rock core, open-hole geophysical, lined-hole hydro-physical) used to design a multilevel system.

	Readily Available		Specialty	
Target	**Primary Tools**	**Secondary Tools**	**Common**	**Limited**
Lithology and mineralogy	▪ Gamma ▪ Conductivity / Resistivity ▪ Spectral gamma	▪ Acoustic televiewer ▪ Video ▪ Optical televiewer ▪ Magnetic susceptibility ▪ Full waveform seismic	▪ Density ▪ Neutron ▪ Vertical seismic profiling	▪ Temperature ALS ▪ FMI ▪ NMR
Weathering	▪ Full waveform seismic ▪ Video	▪ Cross hole seismic ▪ Acoustic televiewer ▪ Conductivity/Resistivity +Gamma	▪ Magnetic susceptibility ▪ Density ▪ Neutron	▪ Vertical seismic profiling
Elastic properties	▪ Full waveform seismic	▪ Vertical seismic profiling	▪ Cross hole seismic	
Porosity		▪ Active temperature ▪ Conductivity / Resistivity	▪ Neutron	▪ NMR ▪ Induced polarization
Bulk Fracturing	▪ Temperature ▪ Acoustic televiewer ▪ Video ▪ Optical televiewer	▪ Caliper ▪ Conductivity / Resistivity ▪ Full waveform seismic	▪ Micro resistivity ▪ Neutron ▪ Density ▪ GPR	▪ Tube wave seismic
Individual Fractures	▪ Acoustic televiewer ▪ Video ▪ Optical televiewer	▪ Caliper ▪ Temperature passive	▪ Temperature ALS ▪ GPR	▪ Tube wave seismic ▪ Micro-resistivity
Orientation of fracturing	▪ Acoustic televiewer ▪ Optical televiewer		▪ GPR	▪ 4 arm dip-meter ▪ FMI
Water Flow cross-connected	▪ Heat pulse flow meter ▪ Impeller flow meter	▪ Temperature open-hole ▪ Video	▪ Temperature ALS	▪ FEC with BH dilution ▪ Electromagnetic flow-meter
Water Flow ambient	▪ Temperature passive lined-hole		▪ Temperature ALS lined-hole	
Water Quality	▪ Conductivity / Resistivity ▪ Water Conductivity	▪ Direct sampler	▪ Ph, DO, Redox, Salinity	
Borehole Properties	▪ Acoustic televiewer ▪ Caliper	▪ Full waveform seismic	▪ Magnetic (+tilt-meter) deviation ▪ Borehole (gyro) deviation	▪ FMI

Table 1. Summary of the primary tools available for detecting or inferring various parameters of the borehole environment.

Note: Emphasis of text (**Regular**/Rare) indicates reliance of the University of Guelph research team on the technique for DFN analysis. Other specialized and/or proprietary tools and techniques exist but are available on a limited basis. Designation of the availability of the techniques is based on a local perspective, what is available, and at what cost. “Specialty” tools are either rarely used or have few practitioners. Techniques that rely on active nuclear sources are designated as “specialty” because of licensing requirements and sensitivity to use in some environments. Some methods also have borehole diameter restrictions. Acronyms: Nuclear magnetic resonance (NMR), Fluid electrical conductivity (FEC), Gamma-Gamma (Density), Ground penetrating radar (GPR), Resistivity Borehole Imaging (FMI).

6. Improved Methodology for Straddle-Packer Hydraulic Testing in Fractured Rock

Patryk Quinn, John A. Cherry, and Beth L. Parker

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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As described in the previous five articles in this series, a comprehensive Discrete Fractured Network (DFN) Approach for investigating contaminated sedimentary rock has recently been developed by researchers at the University of Guelph. A component of this approach involves determination of the hydraulic nature of the borehole, described primarily by the bulk transmissivity (Tb) of the entire borehole and depth-discrete transmissivity (T) values along the length of the borehole. The T values are used to calculate the hydraulic conductivity (K) and the hydraulic aperture (2b). These parameter values are needed as inputs to mathematical models that aid in the understanding of the present contaminant distribution determined from rock core analysis (Article 2 in this series) and predict future contaminant behaviour. Depth-discrete T values are determined from multiple hydraulic tests; aperture values are determined using the cubic law in which the fracture hydraulic aperture is proportional to [T/N], where N is the number of permeable fractures in each test interval.

In the DFN Approach, two types of hydraulic tests used to obtain T values for the borehole are (i) comprehensive hydraulic tests using straddle packers and (ii) flexible liner (FLUTe™) profiling, a new method described in Article 3. These two types of tests are used synergistically; liner profiling covers the entire length of borehole, but comprehensive packer testing equipment is used to obtain more accurate T values in high priority test intervals. Hydraulic tests in boreholes using packers have existed for a long time. However, the method used in the DFN Approach uses advanced equipment and procedures for improved accuracy and precision. In the comprehensive hydraulic tests, hard durable rubber packers are used to isolate a section of the borehole and water is injected or withdrawn from the interval between the packers while measuring the flow rate (Q) and the applied head (dH) in the test interval (Figures 1 and 2).

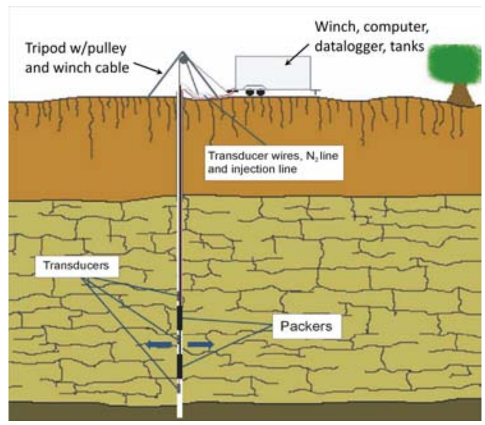

Figure 1. Straddle packer assembly in a fractured rock borehole.

Transducers positioned in the open hole above and below the test interval serve to monitor for hydraulic short circuiting; gum rubber sleeves are fit over the packers to minimize short circuiting between the packers and the borehole wall. This equipment is deemed comprehensive because a suite of hydraulic tests are conducted in each test interval, including constant head step tests, rising and falling head slug tests, pumping tests (injection or withdrawal), and recovery after constant injection or withdrawal (Figure 3). Each type of test can supply unique information regarding the hydraulic nature of the interval. Constant head step tests are ideal for identifying the critical flow rate (Qc) at which flow begins to deviate from Darcian flow. This critical flow rate is used to calculate the critical Reynolds number (Re_c). The T values are calculated using the test results at flow rates below the Re_c where the flow is in the Darcian range and the Re_c is used to aid in the selection of the active number of fractures present in the test interval. Multiple rising and falling head slug tests are used to examine borehole development effects. Pumping and recovery tests can give insight into dual permeability effects and, if both injection and withdrawal tests are conducted, fracture dilation/contraction effects may be examined. Using different mathematical models, such as those shown in Figure 3, a T value is determined from the data from each type of test. Comparison of the T values from the different hydraulic tests provides the best estimate of T and therefore minimizes the uncertainty in the calculated values for hydraulic aperture.

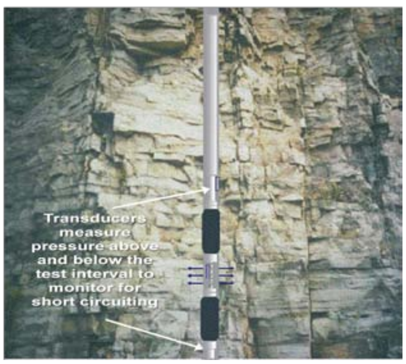

Figure 2. The packers are inflated and water is injected or withdrawn from the interval between the packers.

Prior to the advent of the liner method to obtain continuous K profiles in boreholes (Article 3), continuous profiles were obtained by packer testing the entire borehole length using short intervals (e.g., 1-3 m). However, in this procedure only one type of hydraulic test was used because of the time required to test the entire length of the borehole. Liner profiling of an entire borehole can be completed in a very short period of time, typically less than 3 hours, and under ideal conditions most transmissive features in the borehole are identified. Comprehensive packer testing is usually conducted after liner profiling and geophysical logging are completed. The intervals selected for comprehensive packer testing are chosen based on examination of the liner profile, borehole image logs (e.g., acoustic televiewer, video), high resolution temperature logs in lined holes, and rock core data. Because liner profiling is insensitive at the low end of the T range, packer tests can be used to examine selected low T zones. This is done to seek evidence for the presence of low permeability fractures because contaminant transport commonly occurs in a wide range of fracture types and sizes.

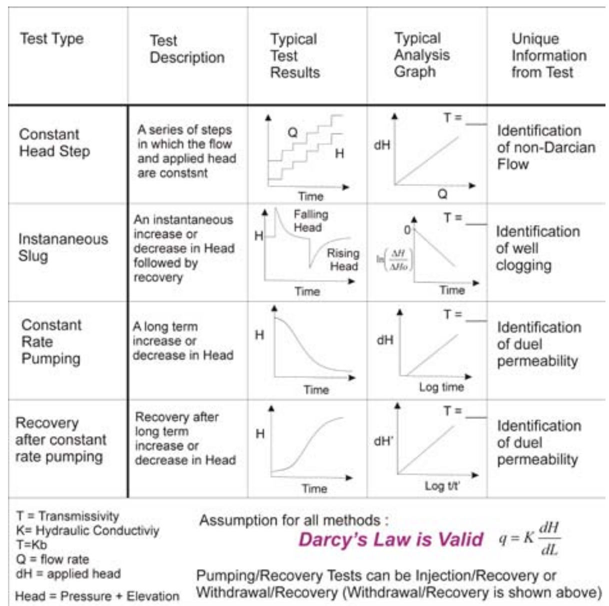

Figure 3. The four types of comprehensive hydraulic tests using straddle packers in fractured rock boreholes.

To obtain hydraulic aperture values for each test interval, the most representative value for T is combined with the best estimate of the hydraulically active fractures present in the test interval using the cubic law. The number of hydraulically active fractures in each test interval is determined by weighing the evidence from all of the available data (e.g., image logs, core log, temperature log, Re_c vs. 2b plot). There is typically more than one fracture present in each test interval, and all fractures are assumed to be the same size; therefore, the calculated aperture is an average value. Typically, the mean hydraulic aperture values at fractured sedimentary rock sites are relatively small, in the range of 50 to 500 microns (for comparison, the average diameter of the human hair is 100 microns). Hydraulic apertures are generally much smaller than many of the apertures estimated using borehole image or video logs. These borehole images pertain to what exists only at the borehole wall, but the hydraulic test results depend strongly on the individual fracture characteristics away from the wall and also on the connections of the fracture at the borehole with other fractures away from the borehole. In the DFN Approach for characterizing contaminated zones in fractured rock, the results from comprehensive straddle packer testing are combined with all other borehole data to obtain the most accurate values for T and 2b as well as develop a statistical spatial representation of the properties of the fracture network. These statistical representations of the fracture network properties are used in the DFN mathematical modelling of groundwater flow and contaminant behaviour.

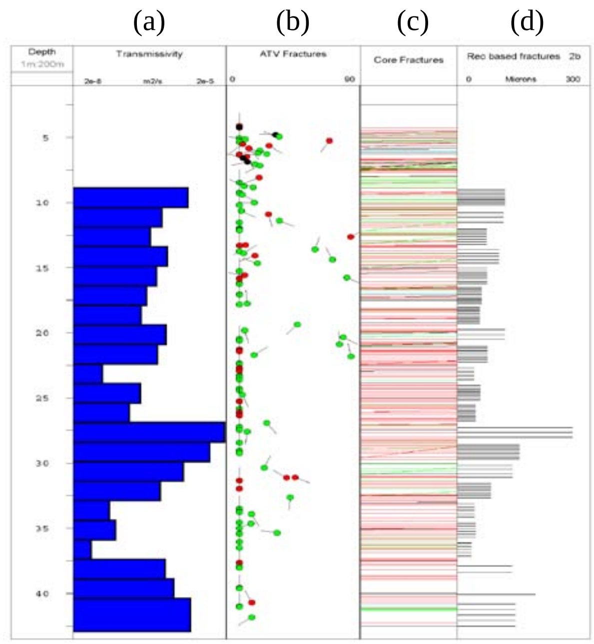

Figure 4. Packer testing example with aperture distribution: (a) T values from packer tests using 5 ft intervals, (b) fractures identified using borehole imaging, (c) fractures identified by core inspection, and (d) aperture values from cubic law calculation.

Associated Publications

Quinn, P.M., J.A. Cherry, and B.L. Parker. 2011. The influence of initial displacement on slug tests conducted in a fractured dolostone aquifer. For submission to the *Journal of Hydrology*.

Quinn, P.M., J.A. Cherry, and B.L. Parker. 2011. Using constant head packer tests to determine apertures in fractured rock. Accepted with minor revisions to the *Journal of Contaminant Hydrology*.

Quinn, P.M., J.A. Cherry, and B.L. Parker. 2011. A versatile packer system for high resolution hydraulic testing in fractured rock boreholes. Submitted to *Ground Water Monitoring and Remediation*.

Quinn, P.M., J.A. Cherry, and B.L. Parker. 2011. Quantification of non-Darcian flow observed during packer testing in fractured sedimentary rock. Submitted to *Water Resources Research*.

7. Design Strategies for High-Resolution Multilevel Monitoring Systems for Fractured Rock Sites

Jessica R. Meyer, Beth L. Parker, and John A. Cherry

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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In the traditional approach to investigations at contaminated bedrock sites, conventional monitoring wells are the primary means for characterizing the nature and extent of contamination. However, in the Discrete Fracture Network (DFN) Approach, rock core contaminant analyses are essential for determining contaminant distributions. Drilling almost always creates vertical cross-connection and redistribution of contaminants in the borehole and, for sedimentary rock, most or nearly all contaminant mass has diffused into the porous but low permeability rock matrix. The DFN Approach uses depth-discrete multilevel systems in addition to conventional monitoring wells to obtain temporal chemistry data from the water flowing in the fractures. A multilevel system (MLS) is an assemblage of pipe/tubes/seals that creates discrete monitoring intervals across specific lengths of the borehole. Seals isolate each monitoring interval to provide depth discrete hydraulic and hydrochemistry information representative of the specific interval in space and time (Figure 1). Specifically, MLSs are designed to collect temporal information on hydraulic head, transmissivity, and water chemistry, both natural and contaminant (Figure 2). Because the water sampled by MLSs is drawn primarily from the fractures, the profiles of water chemistry obtained are different from, but complementary to, those obtained from rock core analyses.

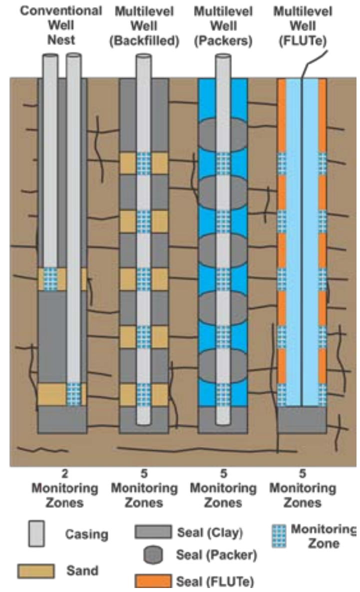

Figure 1. A multilevel system is a single device installed into a borehole that divides the hole into many separate intervals for depth discrete monitoring

Four different types of MLSs are available from commercial suppliers: Water FLUTe™ from Flexible Liner Underground Technologies (FLUTe™), the Waterloo and CMT® Systems from Solinst® Canada Ltd., and the Westbay® system from Schlumberger Canada Ltd. Each of these systems includes a variety of design and equipment options. Choosing a MLS depends on the site specific hydrogeological conditions and the monitoring objectives, with clarity provided by the complementary DFN Approach data sets. Once the type is chosen, the MLS is custom designed for each hole. Customization involves specifying the lengths and positions of monitoring intervals and sealed segments based on data sets collected as part of the DFN Approach (e.g., geological and geophysical logs, high resolution temperature profiles, hydraulic conductivity profiles obtained using the FLUTe™ liner, straddle packer tests). Figure 3 shows an example of the type of borehole information used in the design of a MLS. Commercially-available MLSs can accommodate anywhere from 10 to 40 monitoring intervals in a 500 ft, 4 inch diameter borehole. In conventional practice, however, MLSs are designed with only a few (3-4) monitoring intervals compared to the maximum number possible. In the DFN approach, MLSs are designed so that the number of monitoring intervals is maximized to provide the most detailed data possible and to avoid cross-connection of different aquifer units.

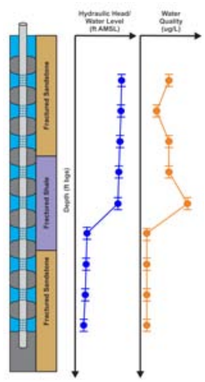

Figure 2. Example hydraulic head and water chemistry datasets collected from a MLS.

Conventional characterization of contaminated bedrock sites occasionally includes the use of straddle packers to obtain profiles of hydraulic head and hydrochemistry; this is in addition to being used to perform hydraulic tests for transmissivity. An interval of the borehole is isolated by inflating the packers and head is measured and/or a water sample is collected. The method is generally avoided in the DFN Approach because experience in many bedrock systems shows that the results are not depth discrete representations of what is obtained when the same type of data are collected using a MLS. This is attributed to the effects of cross-connection from the open hole above and below into the temporary packer sealed interval. For the MLS to provide hydrochemistry representative of the *in situ* formation conditions, sufficient time must pass after installation of the MLS to allow cross-contamination effects to dissipate. MLSs are used as part of the characterization phase of contaminated site studies, but can also be used for long-term groundwater monitoring. Depending on which of these two phases is the focus, a different type of MLS may be used. For example, a MLS that is easily removable (e.g., Water FLUTe™) may be selected for site characterization and redesigned for the monitoring phase. One of the goals of site characterization is development of the knowledge needed to design a network of MLS and/or monitoring wells most suitable for long-term groundwater monitoring. The optimal locations for wells and/or MLSs used for long-term monitoring can only be specified if the groundwater flow system and the nature and extent of the contamination have been appropriately characterized using the DFN Approach.

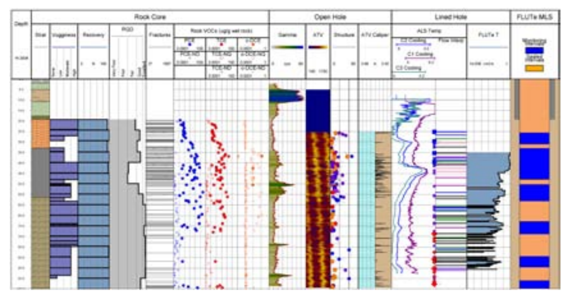

Figure 3. Example DFN datasets used to design a MLS at site #2 in Guelph, Ontario. Data sets from the rock core, open hole, and FLUTe lined hole were used to create a custom designed MLS with six monitoring intervals.

Associated Publications

Cherry, J.A., B.L. Parker, and C. Keller. 2007. A new depth-discrete multilevel monitoring approach for fractured rock. *Ground Water Monitoring & Remediation* 27, no.2: 57-70.

Meyer, J.R., B.L. Parker, and J.A. Cherry. 2008. Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock. *Environmental Geology* 56, no.1: 27-44.

Parker, B.L., J.A. Cherry, and B.J. Swanson. 2006. A multilevel system for high-resolution monitoring in rotasonic boreholes. *Ground Water Monitoring and Remediation* 26, no.4: 57-73.

8. Nature of Organic Solvent Source Zones and Plumes in Fractured Sedimentary Rock

Beth L. Parker, John A. Cherry, Steven W. Chapman, and Jessica R. Meyer

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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The general nature of contaminant plumes in granular geologic media (i.e., porous media such as sand and gravel deposits) is now well established via thousands of contaminated site investigations and detailed field tracer experiments conducted over the past three decades. However, this is not the case for plumes in fractured sedimentary rock (e.g., sandstone, shale, limestone, dolostone) even though most of the population centres of North America are situated on such deposits, which are extensively utilized as water supply aquifers. While many contaminated bedrock sites have been discovered and studied, insights from these investigations have lagged far behind sites on granular deposits due to their additional complexity as well as the lack of high resolution field methods.

Despite the lack of field methods, numerical models first developed in the 1980s included the complexity of fractures and fracture networks and processes for interactions between fractures and the matrix (e.g., FracMan®, Fractran, HydroGeoSphere). However, the computing power was limited and, most importantly, no sufficiently detailed field studies of existing contaminant plumes were available to parameterize or ground truth these models in a field setting.

Field aspects of contaminant hydrogeology in fractured rock have lagged behind porous-media hydrogeology for a few reasons, one of which is the lack of high resolution field methods needed to accomplish comprehensive delineation of the nature and extent of the contamination as previously mentioned. This does not reflect a lack of research concerning flow and contaminant transport in fractured rock. On the contrary, a huge research effort has been directed at fractured crystalline rock (e.g., granite) because of plans for disposal of high level radioactive waste deep in this type of rock in Europe, Canada, and beyond. However, this research has not included study of actual contaminant plumes because they do not exist. Moreover, the characteristics of this type of rock are much different than those of sedimentary rock.

Conventional groundwater studies of fractured sedimentary rock are inadequate for two primary reasons. First, conventional studies are biased toward water supply issues and limited to questions about plume fronts because conventional wells only provide water from the fractures with emphasis on the highest permeability features. Second, conventional studies do not characterize the rock matrix despite the fact that nearly all of the contaminant mass occurs in low permeability rock matrix due to diffusion processes. The lack of rock core contaminant data makes it impossible for conventional studies to characterize plumes in fractured porous rock. Although inadequate for characterization, conventional monitoring wells are appropriate for long-term monitoring if they are positioned based on what is learned during site characterization using the Discrete Fracture Network (DFN) Approach. The DFN Approach, described in Article 1, was developed to provide the scientific / technical possibilities for comprehensive plume investigations by assessing contaminant distributions in both the rock matrix and the fractures and to provide the necessary inputs for application of DFN numerical models. The DFN Approach includes comprehensive sampling of continuous rock core from strategically located holes for contaminant analysis, and then the use of the cored holes for hydraulic tests, borehole geophysics, and installation of multi-level monitoring wells to measure hydraulic head and groundwater contaminant concentrations in numerous depth-discrete intervals. The DFN Approach is being applied intensively at eight contaminated sites on fractured sedimentary rock in North America, including five in the United States on sandstone, siltstone, and shale and three in Canada on dolostone. Although these site characterizations are still in progress, sufficient information has been acquired from each to draw important conclusions concerning contaminant distributions and the processes governing contaminant transport and fate.

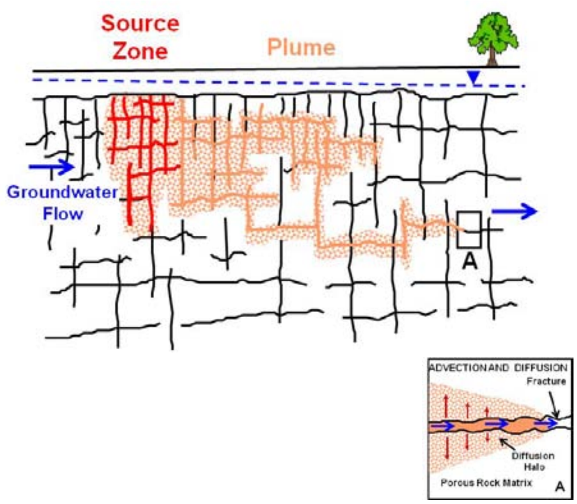

Figure 1. Schematic cross-section view of a plume in fractured sedimentary rock showing DNAPL source zone and downgradient dissolved plume. Contaminant mass is diffusing into the porous rock matrix in the source and plume zones where it resides as dissolved and sorbed phases (inset shows blow-up for an individual fracture at the plume front).

The information collected from these eight field sites is used in this article to outline the general nature of contaminant plumes from 'point sources' in fractured sedimentary rock. Figure 1 depicts a generalized view of a plume in fractured sedimentary rock, showing the 'source zone' where the contaminants initially entered the rock and the plume generated by recharge and groundwater flow through the source zone. The generalizations apply to sedimentary rock in which the rock porosity supports diffusion-driven contaminant mass transfer between the fractures, where active groundwater flow occurs, and the low permeability blocks of porous rock between fractures, where there is high storage capacity and diffusion dominates contaminant movement.

Table 1 summarizes the common features of the eight sites with respect to site contaminants and hydrogeology. The primary contamination entered the rock at these sites beginning decades ago, as dense non-aqueous phase liquids (DNAPLs), and ceased at least a decade and typically longer ago. Table 1 indicates that some of the contaminated sites are on fractured rock aquifers used for public water supply; others are on rock that is moderately permeable but which is not used for water supply in the vicinity of the contaminated sites. Some of the plumes are under the influence of pumping of water supply wells. Plumes of dissolved contaminants from the DNAPL serve as hydrogeologic tracers in the fractured rock to provide understanding of system behaviour. At all sites, the water table is generally shallow, typically 10-50 feet below ground surface. Hydraulic tests and contaminant distributions show that the rock has ubiquitous, closely-spaced fractures that have strong interconnectivity. The rock matrix porosity is generally in the range of 5-20%, which is typical of the range expected for sedimentary rock. However, the assorted rock types exhibit varying degrees of sorption potential within the matrix, governed mainly by organic carbon content for organic contaminants. Estimated values of average linear groundwater velocity in the fracture networks are generally several feet/day or higher, which are large relative to velocities typical for groundwater at contaminated sites on sandy aquifers (0.3-3 feet/day). Although the character and complexity of the fracture networks at the eight sites varies, field investigations show that the bedrock contamination can be readily characterized using the DFN Approach and, therefore, the contaminant plumes are amenable to monitoring. By this we mean that at boreholes

Table 1. Summary of eight sites where the DFN Approach is being extensively applied, including contaminant types, site hydrogeology, and contaminant conditions.

Site	Site Location	Water Supply Aquifer*	Rock Type	Major Parent Chemicals	Degradation Products	Release Period	Water Table Depth (ft bgs)	Maximum Contaminant Depth (ft bgs)	Overburden Thickness and Type (ft)	Cause of Contamination and comments
1	Simi, California	No	sandstone with siltstone and shale interbeds, 30° dip	TCE, minor TCA	cis-DCE, 1,1-DCE, trans-DCE, VC	1950s - 1960s	< 50 to 300 ft	> 1000 ft	0 - 15 ft; alluvium	Rocket engine testing, research; many plumes from many different source areas; no DNAPL found
2	Wisconsin	Not currently operating (public); private wells	sandstone with minor siltstone and dolostone; flat lying	PCE, TCE, TCA, ketones	cis-DCE, 1,1-DCA, 1,1-DCE, VC	1950s - 1960s	0 - 80 ft	most mass < 200 ft (max <300 ft)	20 - 130 ft; glacial sand, silt and clay layers	Solvent recycling; 10,000 gal DNAPL pumped from source zone, residual DNAPL remains
3	South Plainfield, New Jersey	Yes	mudstone; 5-15° dip	PCE, TCE, PCBs	cis-DCE, VC	Facility operating since 1920s; release period unknown	< 10 ft	> 400 ft	0.5 - 15 ft; Glacial deposits (reddish brown silt, sand and clay); fill in some areas	Manufacturing; auto industry parts and electronics; DNAPL observed in one well
4	Watervliet, New York	No	shale, 50° dip	PCE, TCE	cis-DCE, trans-DCE, VC	Facility operating since early 1800's; likely 1950s -1960s for studied plume	<20 ft	> 150 ft	10 - 20 ft; Glacial deposits (dark grey silty sand and gravel)	Manufacturing; military (oldest cannon manufacturing facility in the US); focus on one plume; DNAPL observed in one well in 1990s
5	Union, New York	Yes (private wells)	siltstone with minor sandstone and shale	TCE, petroleum products	cis-DCE, VC	1950s - 1970s	< 5 to 25 ft	most mass < 20 ft (max < 50 ft)	< 5 ft; Glacial deposits (sand and silt)	Chemical disposal in burn pits from off-site manufacturing and lab operations
6	Cambridge, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	Metolachlor, TCE, minor PCE	cis-DCE and metalochlor deg products	1978 - 1990	60 ft	500 ft (into shale aquitard)	80 - 120 ft; Glacial deposits (sand and silt, thin basal till over bedrock)	Agricultural chemical packaging; no DNAPL found
7	Guelph, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	TCE, minor PCE	cis-DCE, VC	1990s	10 - 15 ft	> 300 ft	10 - 20 ft; Glacial till	Manufacturing; auto parts; no DNAPL found
8	Woolwich, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	PCE	TCE, cis-DCE	1950s-1970s	10 - 15 ft	>100 ft	10 - 20 ft; Glacial till and gravel backfill	Former dry cleaner; no DNAPL found

* the plume occurs in very permeable aquifer that provides municipal water nearby

situated where historical site information or other evidence suggests that DNAPLs entered the bedrock, the rock core contaminant analyses show substantial contaminant mass. The contaminant distributions considered in the context of the nature of the groundwater flow system indicate deep contamination caused initially by deep DNAPL penetration. Also at the eight sites, coreholes located in the direction of groundwater flow away from the DNAPL input locations show contaminant mass distributions consistent with simulations using DFN numerical models of the formation of plumes emanating from subsurface source zones in highly fractured, strongly interconnected fracture networks.

The fact that the plumes are readily located using a relatively small number of cored holes is evidence that contaminant transport occurs in a large number of fractures and that transverse dispersion (i.e., plume spreading orthogonal to groundwater flow) is strong relative to what would be expected in granular aquifers, as illustrated conceptually in Figure 2a. The presence of significant mass remaining in the contaminant input locations, but generally at concentrations estimated to be well below contaminant solubility levels, provides support for the strong influence of diffusion on source and plume evolution. The alternative to this finding would be that the plumes are channelled or funnelled into narrow zones due to the dominance of flow in one or a few large, major fractures or fracture zones extending over long distances; in this case, the plumes would become long and narrow or 'snake-like' in shape rather than fan shaped (Figure 2b). These plumes would also extend for significant distances from the input locations. This alternative view of plumes in fractured rock is known as the 'super-highway concept'. Prior to the initiation of these eight contaminated site studies using the DFN method, there was concern that complexities in the geologic structures and fracture network characteristics would be so strong as to cause the subsurface source zones and plumes to be extremely difficult or even practically impossible to locate and delineate. In such a scenario, contaminant distributions would be excessively elusive and not amenable to predictive modelling or reliable monitoring. However, this turns out not to be the case for these eight contaminated sedimentary rock sites. The predictable behaviour of contaminants at these sites is attributed to the strong interplay between the matrix and fractures due to numerous, well inter-connected fracture networks.

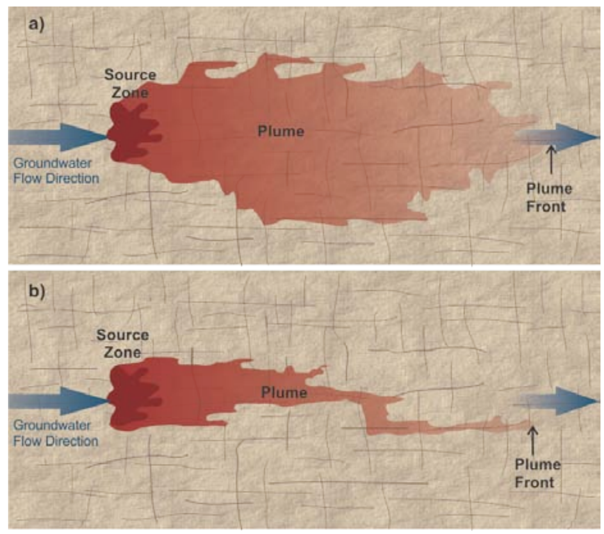

Figure 2. Two conceptual views of plumes caused by DNAPL entry into fractured sedimentary bedrock. The source zone is where DNAPL existed before dissolution and diffusion caused DNAPL disappearance and a plume with dissolved and sorbed contaminants: (a) the plume spreads out to create a fan shape due to transverse dispersion in a strongly interconnected network of many fractures or (b) alternative 'super-highway' view where the plume is funnelled into one or a few major fractures that dominate the groundwater flow over large distances.

While average linear groundwater velocities in fractured rock are relatively large in comparison to velocities in sand and gravel aquifers, the distance travelled by each plume front is much smaller than expected based on consideration of groundwater velocities alone. This difference between predicted distance of groundwater travel and the plume length is known as 'plume retardation'. Plume retardation in fractured sedimentary rock is caused by transfer of contaminants in the groundwater moving through the fractures into the low permeability rock matrix by diffusion. In the rock matrix, contaminant storage is enhanced by sorption. The overall effect of this chemical mass transfer is that the measurable plume front lags substantially behind the calculated groundwater travel distance. As an example, Figure 3 shows results of a DFN simulation using the Fractran model tailored to the California site. For the well-interconnected fracture network (Figure 3a) and imposed average hydraulic gradients of 0.5% horizontal and 0.2% vertical (downward), the simulated contaminant plume after 50 years (Figure 3b) has migrated less than 1000 ft from the source. The plume migration is limited despite an average linear groundwater velocity in the fracture network greater than 10 ft/day, which puts the groundwater travel distance at more than 30 miles from the source zone. Thus, the plume front would extend long distances from the input location if migration occurred at groundwater flow velocities without attenuation via diffusive mass transfer into the matrix. Although the modelling goal is not to perfectly match the field profiles, given the complexity of fractured rock systems, the style of the simulated contaminant profiles compare well with field profiles collected using rock core sampling (Figure 3c), which provides increased confidence in the model simulations.

Although this matrix diffusion effect causes the horizontal extent of the plume fronts to be much smaller than expected based solely on the groundwater velocity estimates, plume bottoms are still quite deep at most of the sites (Table 1). The plume bottoms are deep because of the propensity for DNAPL, the initial cause of the subsurface contamination, to descend downward through interconnected fractures. Figure 4 shows conceptual stages of source zone and plume evolution in fractured sedimentary rock. At all of the sites except one, the DNAPL mass that was the initial cause of plume generation (Figure 4a) has mostly or entirely transformed into dissolved and sorbed mass now residing in the rock matrix blocks between fractures. Therefore, there is no difference in the state of the contaminant mass between the former DNAPL source zones and the plumes (Figure 4b). For all eight of these sites, groundwater contaminant transport occurs almost exclusively through the fractures, but nearly all of the contaminant mass is situated in the rock matrix. Contaminants are still diffusing into the rock matrix blocks in some zones and outward diffusion occurs back into the fractures in other zones. Such slow outward diffusion causes contaminants to persist in the former DNAPL source zones for extended periods of times (decades to centuries) despite complete disappearance of the original DNAPL mass due to dissolution and diffusion. Therefore, the scenario represented by Figure 4c with mass depleted from the former source zone may only occur after very long time periods on the order of centuries. An important implication of this understanding of the contaminant mass residing mostly or nearly entirely in the low permeability rock matrix, rather than in the fractures, is that remedial efforts to return the groundwater to drinking water standards requires removal of essentially all of the rock matrix contaminant mass.

The investigations using the DFN approach at the eight sites are still in progress, and not all of these plumes have been comprehensively delineated. However, abundant evidence from each site supports the general conceptual model presented here for organic contaminant plumes in fractured sedimentary rock, where ubiquitous hydraulically active fractures surrounded by porous rock matrix dominate groundwater flow, and diffusion processes in the rock matrix strongly influence contaminant transport. At the dolostone sites, solution channels (i.e., karst features) are evident but no evidence indicates that channelled flow in these features governs plume behaviour. Table 1 indicates that chlorinated solvents are the primary contaminants of concern at seven of the eight sites, where typical microbial degradation

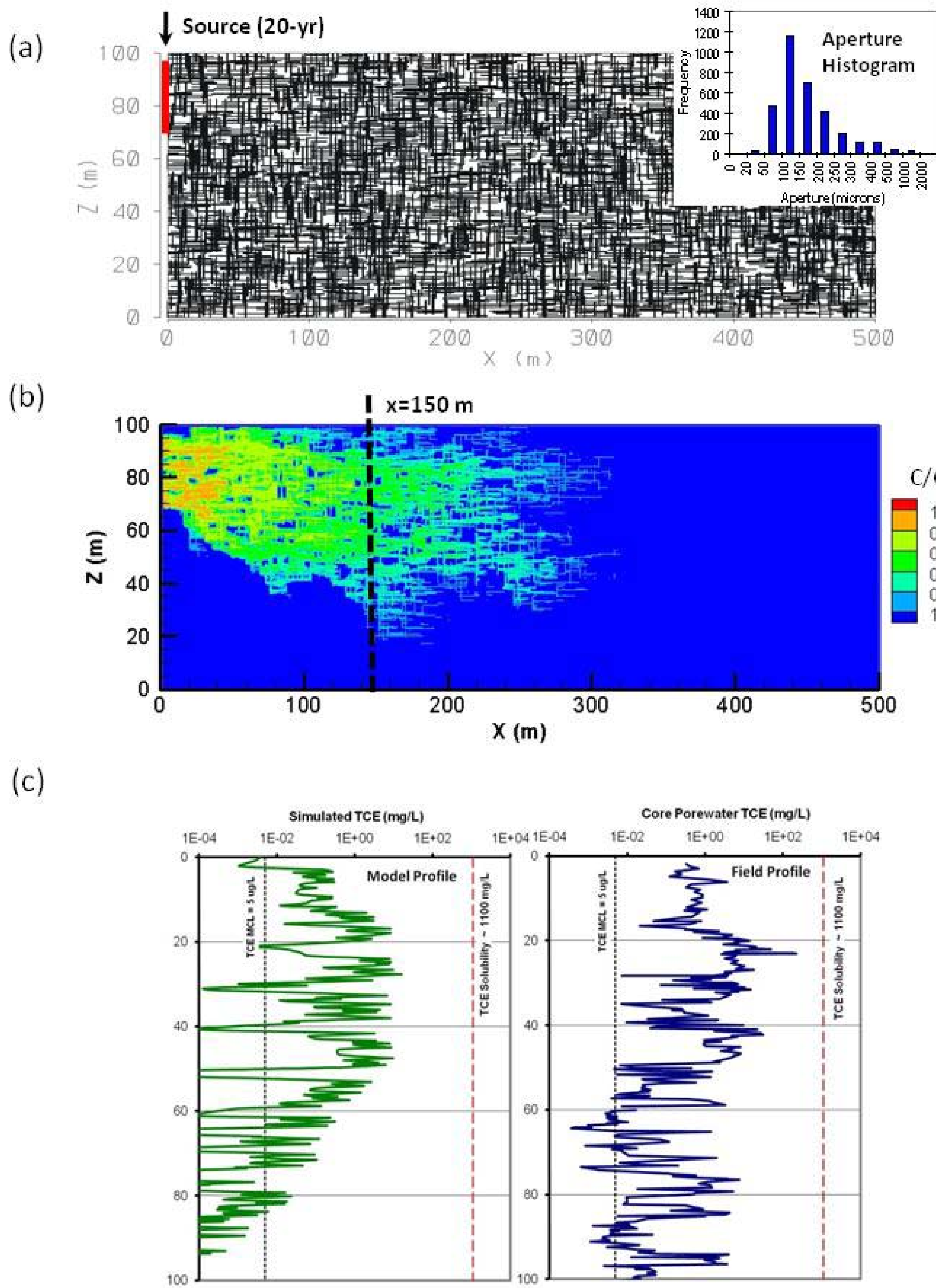

Figure 3. Example of DFN simulation showing plume characteristics: (a) model domain and fracture network for a scenario with a well-interconnected fracture network with inset showing statistical distribution of fracture apertures and position of the source, which is assumed constant for a 20 year period representing the period of DNAPL presence, (b) simulated plume contours after 50 years, and (c) comparison of simulated contaminant profile at X=150 m with measured contaminant profiles at the California site, showing similarity in the nature of the profiles.

products occur and thus indicate that the parent chemicals have undergone mass reduction due to degradation. There is evidence that some or much of this degradation occurs in the rock matrix.

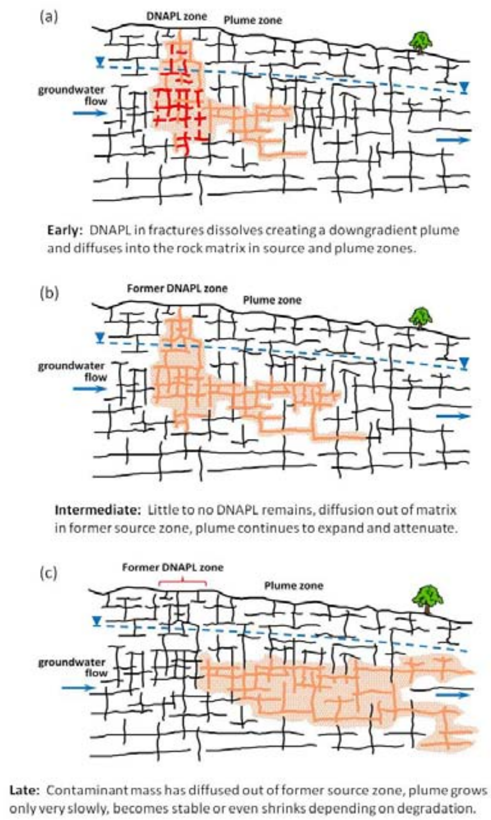

Figure 4. Illustration of conceptual stages of source zone and plume evolution for chlorinated solvents in fractured sedimentary rock: (a) early stage with DNAPL achieving a stationary position in fractures and dissolution causing formation of a downgradient plume with contaminant mass diffusing into the rock matrix; (b) intermediate stage with most or all DNAPL mass dissolved away and nearly all mass existing in the rock matrix as dissolved and sorbed phase. Diffusion out of the rock matrix occurs within the former source area and the plume continues to expand and attenuate; and c) late stage with groundwater flow through the former source zone causing mass translocation from much of the former source into the downgradient plume. The plume front is migrating only slowly or is stable or even shrinking due to combined effects of matrix diffusion and degradation.

Research in progress is examining the degradation processes and the degree to which the degradation contributes to the natural attenuation of the plumes. The details differ from site to site; however, the features described above imprint a strong commonality in the characteristics of the contaminant distributions, transport, and fate. Although the field data pertain to organic contaminants, primarily chlorinated solvents, one of the sites includes other contaminants (perchlorate and tritium) that are also being investigated using the DFN Approach. The plume behaviour of these contaminants is similar to organic contaminant behaviour, which is expected because the strength of diffusion on all dissolved contaminants is nearly the same. The general nature of contaminant plumes in fractured sedimentary rock described in this article is based on a relatively small number of investigated plumes, as compared to the large number of porous-media plumes that have been investigated in detail. Therefore, we can expect that the robustness of the field-based scientific support for these general conclusions will expand substantially in the future as the DFN Approach is applied at more sites.

Associated Publications

Parker, B.L., S.W. Chapman, J.A. Cherry, K.J. Goldstein, A. Vitolins, D. Navon, and G. Anderson. 2011. A conceptual model for the fracture networks in contaminated shale based on multiple lines of evidence. For submission to *Ground Water*.

Perrin, J., B.L. Parker, and J.A. Cherry. 2011. Assessing the flow regime in a contaminated fractured and karstic dolostone aquifer supplying municipal water. Submitted to *Journal of Hydrology*.

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Plett, J.H. 2006. Metolachlor and TCE Plume Characteristics in a Dolostone Aquifer Using a Transect. Master's thesis, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON.

Zimmerman, L.K. 2010. New opportunities for groundwater hydrochemistry and degradation investigations provided by the SNAP Sampler®. Master's thesis, School of Engineering, University of Guelph, Guelph, ON.

9. Static and Dynamic Modelling Based on DFN Characterization at Contaminated Bedrock Sites

Beth L. Parker, John A. Cherry, Steven W. Chapman, and Jessica R. Meyer

Center for Applied Groundwater Research
University of Guelph
Guelph, ON N1G 2W1

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The purpose of applying the Discrete Fracture Network (DFN) Approach at contaminated fractured rock sites is to develop reliable site conceptual models (SCMs) and related mathematical models to serve as the framework for decisions concerning longer term monitoring, remediation, and site management. The mathematical models for groundwater flow and contaminant transport and fate are used to represent the present state of contaminant distributions, make future predictions of contaminant transport and fate, and evaluate remediation alternatives and efficacy. However, mathematical models for groundwater flow and contaminant transport are only as good as the conceptual models on which they are based; therefore, the development of the SCM is the most important step in the overall modelling process. The SCM for contaminant distribution, transport, and fate is the culmination / integration of conceptual models for site geology, hydrogeology, and hydrogeochemistry. When the DFN Approach is initiated at a contaminated bedrock site, considerable information typically exists concerning the site geology, contaminants of concern, depth to the water table, gross nature of the permeability distribution, groundwater recharge, and rock matrix porosity. The onset of application of the DFN Approach begins with drilling a few cored holes with high resolution and depth discrete rock core contaminant analyses and borehole testing. The selection of the locations and depths of these holes is based on the initial SCM or multiple models (i.e., multiple hypotheses concerning the features and processes affecting contaminant migration and fate at the site). Each new hole drilled is a test of the current SCM. If the information from the new hole does not support this SCM, the SCM is altered or refined. The refined SCM is then tested by drilling additional holes. This process continues until uncertainties in the SCM are acceptable relative to the decisions required.

Each DFN cored hole generates a large amount of data of many diverse types, and this presents a much greater challenge in terms of data management and display than a drill hole in the conventional approach to fractured rock investigations. Therefore, the foundation for the use of DFN data in mathematical models is the compilation, storage, and management of the borehole data in a relational database system created specifically for this purpose. The data management system accommodates the many types of corehole data, including core logs, geophysical logs, temperature and K profiles, hydraulic tests, and that from multilevel systems and monitoring wells. The data management system is essential to the appropriate and efficient display of DFN data in one dimensional (i.e., profiles) or two-dimensional (i.e., transects) forms in software, such as WellCad, Viewlog, or ArcGIS, and in two- and three-dimensional static models, such as Petrel or FracMan. Emphasis on static modelling to represent geology and assist in the delineation of hydrogeologic units is an important step prior to dynamic groundwater flow and contaminant transport modelling.

The ultimate goal of the mathematical modelling is simulation of contaminant transport and fate. This modelling must be done using DFN numerical models in which the transport processes in both the fractures (advection and dispersion) and the rock matrix blocks between fractures (diffusion, sorption, and reactions in most cases) are adequately represented. However, the framework for the DFN modelling is established by groundwater flow modelling, based on the premise that the flow system in fractured rock can be adequately represented by an equivalent porous medium (EPM). This is a reasonable premise for representing bulk groundwater flow for sites where the fractures are ubiquitous and form an interconnected network. When sufficient amounts of data have been acquired, the groundwater flow system is represented in a calibrated three-dimensional groundwater flow model (e.g., using software such as MODFLOW or FEFLOW). Although three-dimensional numerical DFN models for contaminant transport exist (e.g., HydroGeoSphere, FEFLOW, FracMan-MAFIC), none has been shown capable of representing fractured rock domains large enough to encompass actual plumes at the field scale in 3-D. Therefore, the practical approach at present is to apply 2-D DFN simulations to represent plume evolution and predict future plume behaviour. Groundwater flux and hydraulic boundary conditions for the 2-D DFN transport simulations are obtained from the calibrated 3-D groundwater flow model. The 2-D planes (e.g., plan view or vertical cross-sections; Figure 1) used for the DFN modelling are presented according to guidance provided by examination of the flow field produced by the 3-D EPM groundwater flow model.

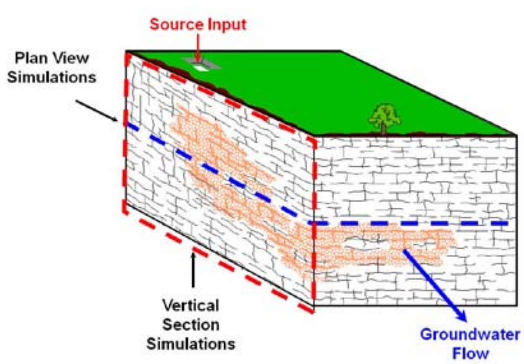

Figure 1. Schematic of a plume in fractured sedimentary rock and how 2-D slices are used for DFN simulation of groundwater flow and contaminant transport in plan view or vertical cross-section.

In DFN transport modelling, the fracture network is represented based on statistical distributions of fracture properties (frequency, length, aperture, orientation). Field and laboratory data collected during DFN investigations, including characteristics for individual fractures (e.g., hydraulic apertures), fracture networks (e.g., fracture spacing and orientation), and rock matrix properties (e.g., distributions of porosity and organic carbon content), are used as input parameters for the DFN simulations. Fracture networks are generated using statistical inputs for fracture network properties and the results of the 3-D groundwater flow model are used to constrain flow in the 2-D fracture networks. The 2-D fracture networks can be adjusted by modifying their characteristics (e.g., fracture frequency, length and aperture distributions) within reasonable ranges. Once reasonable fracture networks are generated and the 2-D DFN flow simulation results are consistent with the 3-D EPM flow system results, the 2-D DFN models are used for simulating contaminant transport and fate. Figure 2 shows an example of a DFN simulation using the Fractran code for a vertical cross-section fracture network, including vertical profiles of hydraulic head and contaminant distribution and integrated data for a hypothetical multilevel monitoring well. The simulated DFN profiles can be stylistically compared with field profiles collected using the DFN Approach. Contaminant distributions generated by the 2-D DFN model are recognized as simplifications of reality, because they are 2-D and not 3-D and because the statistical generation of the fracture networks cannot capture the full complexity and heterogeneity of the actual fracture networks at the field sites (e.g., assumptions of parallel plate fractures). As in all models, there are also necessary assumptions and simplifications that must be kept in mind when using model outputs. However, 2-D DFN simulations tailored to specific sites using this methodology can produce contaminant distributions that are stylistically similar at the appropriate spatial scales to actual rock core and groundwater measurements made at these sites. This approach to modelling the contaminant distributions has been found to play an important role in assessing the site conceptual models and as a predictive tool for informing expectations for future contaminant behaviour or assessing timescales for remediation.

Associated Publications

Parker, B.L., S.W. Chapman, and J.A. Cherry. 2010. Plume persistence in fractured sedimentary rock after source zone removal. *Ground Water* 48, no.6: 799-808.

Sudicky, E.A. and R.G. McLaren. 1992. The Laplace transform Galerkin technique for large-scale simulation of mass transport in discretely fractured porous formations. *Water Resources Research* 28, no.2: 499-514.

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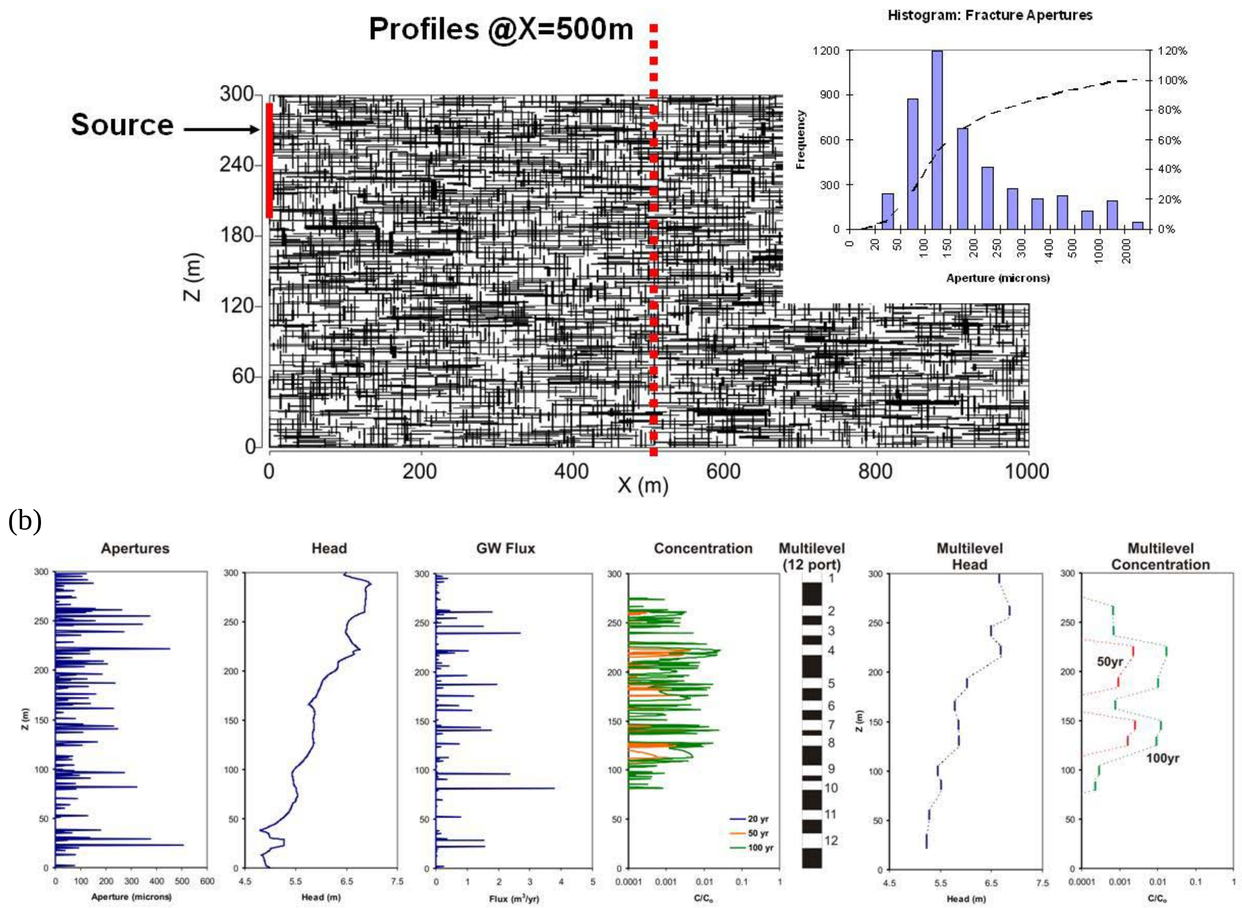

Figure 2. Example of 2-D vertical cross-section DFN simulation results using the Fractran code: (a) model domain, fracture network, and aperture distribution and (b) simulated profiles at x=500 m showing fracture distribution, hydraulic head, groundwater flux, and simulated TCE concentrations at times of 20 years (before TCE arrival at this position) and then at 50 and 100 years, along with integrated head and concentration profiles for a hypothetical multilevel well.