Discrete Fracture Network Approach for Studying Contamination in Fractured Rock

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

Abstract: A comprehensive methodology, referred to as the Discrete Fracture Network (DFN) approach for investigating contaminated sites on fractured sedimentary rock has evolved through intensive studies at several industrial sites contaminated with chlorinated solvents. The approach is directed at acquiring complementary datasets from cored holes with many diverse types of measurements, including core analyses of contaminant distribution and physical, chemical and microbial properties of the matrix, and also corehole tests focused on the nature of the fracture system. Ultimately the goal of this approach is to acquire field and laboratory data necessary for application of DFN numerical models for simulation of groundwater flow and contaminant transport and fate incorporating relevant controlling processes. These studies have provided the basis for development of a general conceptual model for contaminant behavior in fractured sedimentary rock wherein the matrix porosity (typically 2-20%) provides large storage for dissolved and sorbed phase contaminants. Diffusion has driven contaminant mass from the fractures where active groundwater flow occurs into the low permeability rock matrix blocks. This mass transfer combined with the aged nature of these sites results in nearly all contaminant mass now residing in the rock matrix. The fracture networks are also shown to be dense and interconnected which enhances contact between fractures and matrix. As a consequence the resulting contaminant plumes are orderly and small relative to what would be expected from large groundwater velocities in the fractures. The limited plume extent is due to strong matrix diffusion with sorption, transverse lateral spreading in fracture networks and in some zones, contaminant degradation. These processes can be represented in DFN model simulations which have been shown to generate simulated plume conditions that represent the style of contaminant distributions and magnitude of plume attenuation when informed and constrained by site-specific parameters obtained using the DFN approach..

Keywords: fracture networks, sedimentary rock, site characterization, chlorinated solvents, diffusion, solute transport

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Riassunto: *L'articolo tratta di una metodologia integrata per investigare i siti contaminati localizzati su rocce sedimentarie fratturate, denominata "approccio DFN (Discrete Fracture Network), la metodologia viene sviluppata a partire da indagini approfondite, condotte su 8 siti industriali contaminati, situati negli Stati Uniti ed in Canada. L'approccio è una combinazione di metodi di campo, di cui molti sono innovativi e pochi sono miglioramenti di tecniche consolidate e considerate già mature; la fase di affinamento dell'approccio è ancora in corso. L'approccio è diretto ad acquisire data-set integrati di parametri, tramite vari tipi di misure, a partire da carotaggi. Tali misure possono riguardare sia le carote prelevate, comprendendo analisi dei contaminanti e delle proprietà fisiche, chimiche e biologiche della matrice rocciosa, sia il foro di sondaggio, focalizzandosi sulla natura del sistema di fratture e delle sue interazioni con la matrice. I data-set ottenibili da ogni foro sono assai diversi per tipologia e quantità di informazioni; per tale motivo è stato creato un sistema informativo relazionale di immagazzinamento e gestione del dato al fine di facilitare le procedure di QA/QC e di favorire la trasparenza e la tracciabilità. Il fine ultimo di questo approccio è quello di acquisire i dati di campo e di laboratorio necessari per l'implementazione di modelli numerici DFN, in primo luogo modelli statici avanzati (es. Petrel) ed in secondo luogo modelli dinamici (es. FRACTRAN, HydroGeoSphere) ai fini della simulazione del flusso di falda e del trasporto e destino dei contaminanti. Tutti i parametri necessari per la caratterizzazione delle fratture e della matrice rocciosa sono misurati secondo una o più modalità usando sia le carote che il foro, ad eccezione della lunghezza delle fratture. Le distribuzioni della lunghezza delle fratture sono inferite dall'analisi di dettaglio della distribuzione dei contaminanti, impiegando sia l'osservazione diretta nelle carote sia la simulazione calibrata con approccio DFN; in quest'ultima la conducibilità idraulica media dell'ammasso è assegnata in prima istanza a partire dall'analisi di prove di pompaggio e successivamente calibrata tramite simulazioni numeriche tridimensionali di flusso con approccio EPM (Equivalent Porous Medium). Rocce sedimentarie densamente fratturate rappresentano il substrato geologico degli 8 siti indagati, tutti contaminati da inquinanti organici, per lo più solventi clorurati. La porosità della matrice di queste rocce (arenarie, siltiti, argilliti o dolomie), tipicamente compresa fra il 2 ed il 20%, agisce da grosso volume di immagazzinamento per i contaminanti in fase disciolta. La diffusione ha guidato il trasporto di massa di contaminante dalle fratture, laddove avviene un flusso attivo di falda, verso i blocchi di matrice a bassa permeabilità. Questo trasferimento di massa, combinato alla lunga storia della contaminazione di questi siti, ha fatto sì che quasi tutta la massa del contaminante ora risieda entro la matrice rocciosa. I plume di contaminazione che ne risultano sono regolari di forma e piccoli rispetto a quanto ci si sarebbe potuto aspettare sulla base della elevata velocità di flusso associata alle fratture. La limitata estensione dei plume è dovuta alla forte diffusione nella matrice, associata ad adsorbimento, oltre che alla migrazione laterale trasversale nella rete di fratture e, in alcuni siti, alla degradazione dei contaminanti. L'applicazione di modelli di trasporto bi-dimensionali di tipo DFN, che incorporano i processi rilevanti che coinvolgono sia le fratture che la matrice, fornisce la base per quantificare i fenomeni suddetti. Laddove implementati e calibrati tramite parametri sito-specifici ottenuti tramite l'approccio DFN e tramite codici numerici tridimensionali di flusso di tipo EPM, i modelli DFN sono stati impiegati per generare plume simulati che rappresentino la distribuzionedella contaminazione e quantifichino l'attenuazione naturale.*

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Introduction

Groundwater flow analysis in fractured rock is most commonly addressed using the 'equivalent porous medium' (EPM) assumption, which is satisfactory for many types of flow problems. However for assessment of contaminant transport and fate, approaches based on discrete fracture network (DFN) concepts are generally necessary (NRC, 1996; Lapcevic et al., 1999; Berkowitz, 2002). Nearly 15 years ago a major field focused program aimed at improved investigation methods for delineating and understanding the evolution of organic contaminant source zones and plume fate and transport in fractured sedimentary rock was initiated at the University of Waterloo, and since 2007 the program has been based at the University of Guelph. The field efforts began in 1996, when intensive studies were initiated at a TCE contaminated site on steeply dipping and faulted sandstone near Simi Valley, California. Now, with collaborations involving several disciplines (analytical chemistry, mathematical modeling, geophysics, microbiology) the program includes seven additional sites contaminated primarily with chlorinated solvents (Table 1): a Wisconsin site on flat-lying sandstone and dolostone, two sites in New York State and one in New Jersey on siltstone and shale and three sites in Ontario on flat-lying dolostone. These sites have important differences so overall are broadly representative of sedimentary rock, but also several aspects in common including: much data from earlier conventional investigations, contamination initially caused decades ago by DNAPL and therefore these are 'aged' sites, sufficient matrix porosity (2-20%) allowing diffusion-driven chemical mass transfer between fractures and the rock matrix causing strong influence on contaminant behavior, and each site receives much regulatory attention. Diffusion and other processes have caused the plume fronts to advance at rates much slower than groundwater velocities in the fracture networks (Figure 1).

From this research a comprehensive approach has evolved, referred to as the Discrete Fracture Network (DFN) Approach, for investigating sites on sedimentary rock such as sandstone, siltstone, shale, limestone and dolostone. This research has resulted in development of a general conceptual model for the formation and long-term evolution of source zones and plumes in fractured sedimentary rock (Figure 1). Nearly all sedimentary rock has substantial effective matrix porosity (generally 2-20%) allowing contaminant mass to readily diffuse into the matrix in the early decades of contamination, and out of the matrix in later decades or centuries. Although it is typical that nearly all groundwater flow occurs in the fracture network, at 'aged' contaminated sites most contaminant mass now resides in the much lower permeability matrix blocks between fractures. Therefore, the DFN Approach emphasizes using rock core to delineate the contaminant distributions in the matrix and on investigations of the fracture network. Although the DFN Approach had been developed specifically for sedimentary rock, it is relevant to all rock types; however, the rock core sampling approach must be adjusted to suit the nature of the matrix porosity, sorption, contaminant type and time for diffusion. Conventional approaches for investigating fractured sedimentary rock are inadequate because they are biased toward answering questions most relevant to groundwater quantity and water supply. Therefore, the rock matrix is ignored and most of the fractures with active flow and transport go unrecognized. The lack of rock core contaminant data makes it generally impossible for conventional studies to characterize plumes in fractured porous rock.

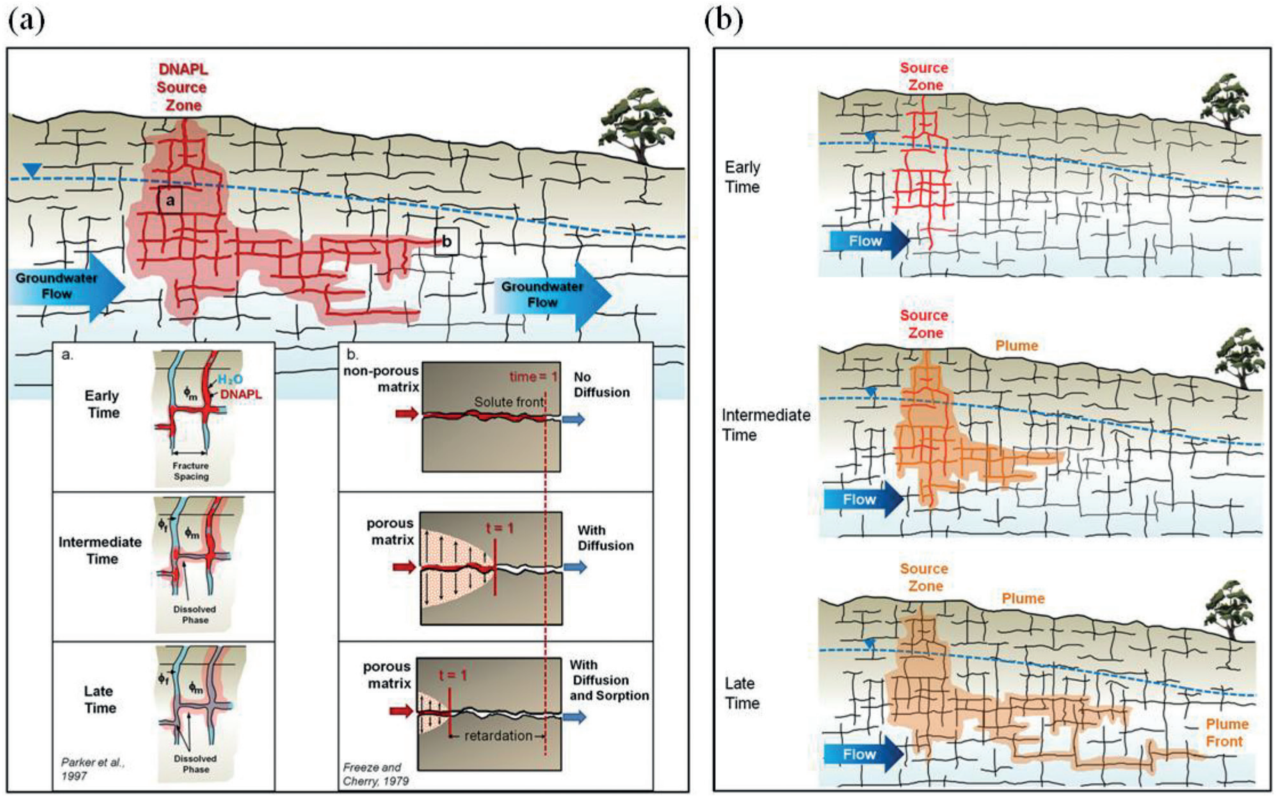

Fig. 1*: Conceptualization of source zone and plume evolution in fractured sedimentary rock: (a) schematic cross-section showing DNAPL release with formation of a downgradient plume, with insets showing source zone evolution (adapted from Parker et al., 1997) and diffusion effects on contaminant migration (adapted from Freeze and Cherry, 1979), and (b) conceptual stages of source zone and plume evolution (adapted from Parker et al., 2010).*

History of DFN Models and Analysis

It is essential in the DFN approach that the methods and models view the rock as having a network of discrete fractures where the spacing, length, orientations, apertures and related hydraulic head distributions and permeability are the focus of field measurements. The earliest origins of many of these measurement methods lie in geotechnical engineering. Snow (1965) introduced the Cubic Law to estimate hydraulic aperture values from hydraulic tests in boreholes, with a goal of determining the interconnected fracture void space related to grouting at dam sites. To account for atmospheric tritium distributions in fractured chalk in the UK, Foster (1975) introduced the concept of diffusion-driven mass transfer from discrete fractures, where nearly all flow occurs, into the low permeability rock matrix blocks between fractures. For fractured porous media including sedimentary rock and fractured clayey deposits, Freeze and Cherry (1979) drew attention to the broader importance of matrix diffusion involving discrete fractures in contaminant hydrogeology. Gale (1982) drew attention to the need to do hydraulic testing in a manner that provides insight concerning fracture hydraulic properties. Concepts for contaminant transport in fractured geologic media where the matrix has substantial interconnected porosity were advanced earliest through investigations in fractured, non-indurated clayey deposits where it was relatively easy to conduct experiments and monitor contaminant migration in shallow zones (<10 m) (e.g. McKay et al., 1993) during field experiments and use large cylindrical soil columns extracted from excavations for laboratory experiments (e.g. Grisak et al., 1980). These fractured clay environments served as close analogs for fractured sedimentary rock.

The first multilevel monitoring system (Westbay) for obtaining detailed profiles of water pressure (head) in rock boreholes was developed for study of mountain slope stability, where it is necessary to know the locations of the porewater pressures most conducive to slope instability. Later this system was adapted for groundwater contamination studies (Black et al., 1986). Also in the 1980s borehole geophysics advanced markedly, with borehole televiewing as a means of 'seeing' fractures becoming important in fractured rock site studies. It was not until the 1980s that mathematical models for groundwater flow and contaminant transport in discrete fracture networks achieved major advances driven mainly by the need to predict radionuclide transport in discretely fractured crystalline rock (e.g. Rouleau, 1984; Long and Billaux, 1987; NRC, 1996). Beginning in the early 1990s, numerical models incorporating random fracture networks and also matrix diffusion became available (e.g. Sudicky and McLaren, 1992; Therrien and Sudicky, 1996). However, although there was an immense effort internationally directed at predicting radionuclide transport in crystalline rock, and through this effort DFN concepts and some field methods were strongly advanced, this effort lacked the opportunity to investigate actual contaminant plumes because the deep rock repositories that were the focus of the effort were only conceptual; no such repositories and no actual radionuclide plumes existed for model verifications.

General Conceptual Model

The development of the DFN approach for investigating contaminated sites on sedimentary bedrock began with an initial conceptual model for contaminant distributions and behavior. This conceptual model, displayed in Figure 1, was based on the premise that, at sites where the contaminants have been in the rock for many years or decades, diffusion-driven chemical mass transfer has caused much or nearly all of the contaminant mass to be relocated from fractures, where nearly all groundwater and non -aqueous phase liquids (NAPL) flow occurs, into the low permeability rock matrix blocks between the fractures, where groundwater is essentially stagnant. This initial conceptual model was based on analytic (Parker et al., 1994; 1997) and numerical modeling (Vanderkwaak and Sudicky, 1996) of chlorinated solvent DNAPL dissolution and diffusion effects and expectations for plume evolution in fracture networks in porous rock with representative rock matrix properties. Based on this model, the goal of determining the contaminant mass distribution must be accomplished by determining the contaminant mass present in low permeability rock matrix blocks between the fractures.

DFN Field Approach Development and Components

The DFN field approach, which was first applied in 1996 at a site near Simi Valley, California on interbedded sandstone and shale, is now well demonstrated in the US and Canada. To date it has been comprehensively applied at eight contaminated sites in sedimentary bedrock including sandstone (2), dolostone (3), shale (2) and siltstone (1) where chlorinated VOCs are the primary contaminants of concern (Table 1). At these sites the contaminants act as tracers of the flow system and transport processes occurring over several decades under natural gradient conditions. Investigations are continuing at most of these sites. The information collected from these eight sites forms much of the supporting basis for the general conceptual model for contaminant plumes from 'point sources' in fractured sedimentary rock (Figure 1). The DFN Approach was developed to take advantage of numerical models that became available in the 1990s for simulation of groundwater flow and contaminant transport in discrete fracture networks with porous rock matrix blocks between fractures (e.g. Sudicky and McLaren, 1992; Therrien and Sudicky, 1996). Previously, these models had not been used to represent real-site conditions due to the lack of suitable field data. The DFN approach combines field data and numerical model application to advance site conceptual models (SCMs) that can serve as the basis for contaminated site decision-making regarding contaminant fate, assessment of risk to receptors and evaluating remediation feasibility and designs. This approach is based on the premise that characterization of contaminated sites and SCM development should be separate from, and prerequisite to, design of long-term monitoring networks.

The following major categories of activities constitute the DFN Approach:

1. rock core chemical analyses and rock matrix properties,
2. use of liners for sealing boreholes and transmissivity measurements,
3. high resolution temperature profiling in sealed holes for identifying hydraulically active fractures without effect of borehole cross-connection,
4. borehole geophysics for rock properties and fracture conditions,
5. straddle-packer hydraulic testing,
6. high-resolution multilevel monitoring systems for hydraulic head and groundwater sampling,
7. data storage/management in a comprehensive relational database system, and
8. static and dynamic modeling.

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Tab. 1: *Summary of eight sites where the DFN approach is being extensively applied.*

Site	Location	Water Supply Aquifer?	Rock Type	Major Parent Chemicals	Degradation Products	Approximate Release Period	Water Table Depth (m bgs)	Maximum Contaminant Depth (m bgs)	Overburden Thickness and Type (m)	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	< 15 to 100 m	> 350 m	0 - 5 m; alluvium	Rocket engine testing, research; many plumes from many different source areas; no DNAPL found
2	Wisconsin	Yes	sandstone with minor siltstone and dolostone; flat lying	PCE, TCE, TCA, ketones	cis-DCE, 1,1-DCA, 1,1-DCE, VC	1950s - 1960s	0 - 25 m	most mass < 60 m (max <100 m)	5 - 40 m; 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	< 3 m	> 120 m	0.1 - 5 m; 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	<6 m	> 50 m	3 -6 m; 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	< 2 to 7 m	most mass < 6 m (max < 15 m)	< 2 m; 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	~20 m	150 m (into shale aquitard)	25 - 40 m; 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	3 - 5 m	> 100 m	3 - 6 m; Glacial till	Manufacturing; auto parts; no DNAPL found
8	Guelph, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	PCE	TCE, cis-DCE	1950s-1970s	3 - 5 m	>30 m	3 - 6 m; Glacial till and gravel backfill	Former dry cleaner; no DNAPL found

The flow chart in Figure 2 summarizes the many components of the DFN Approach; the left side displays observations and measurements made using rock core and the right side shows measurements made in the corehole. In each hole, the DFN Approach emphasizes determining all of the fractures through which groundwater flow occurs under ambient conditions. Results at eight sites on sedimentary bedrock show that contaminant distributions can be explained only if groundwater flow and contaminant transport occur in a multitude of interconnected fractures. Therefore, improved sensitivity for identifying hydraulic activity in as many fractures as possible under natural conditions is key. Table 2 provides an overview of the various techniques utilized in the DFN Approach, and each is described in more detail below. Some components of the DFN Approach continue to be refined and new methods identified; however, the results obtained to date from the eight field sites provide a well established suite of methods and insights for this science-based framework for decision making regarding the transport and fate of contaminants, remediation, and long-term monitoring. The approach is now sufficiently advanced for application at many more sites.

Two elements clearly distinguish the DFN Approach from conventional approaches: (1) use of rock core for contaminant analyses (Figure 3), and (2) use of flexible-impervious liners to (i) seal holes to prevent cross-connection, (ii) measure transmissivity profiles while the liner is installed, and (iii) allow high resolution temperature measurements inside the water filled liner to identify hydraulically active fractures while avoiding the masking effects of vertical connectivity. The DFN Approach avoids using data collected from partially or fully cross-connected open holes because such data tends to be misleading. To combat cross connection, emphasis is directed at minimizing the length of time the core hole is left open after drilling. Although the hole can be used for open-hole geophysics and hydraulic tests, the time allocated for open-hole data acquisition is purposefully limited. Immediately after the hole is drilled, a liner is installed using a procedure that provides transmissivity and hydraulic conductivity profiles (Keller et al., 2011). High resolution passive or active temperature profiling is then done inside the liner as a sensitive tracer of active groundwater flow in sealed (i.e. ambient) conditions (Pehme et al., 2010). The liner is removed for a short period at a later date to allow open-hole geophysical measurements and hydraulic tests. 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) or conventional monitoring well can be installed, from which more data are acquired. These data are used as part of the site characterization, which includes assessment of various hypotheses and development of a robust site conceptual model (SCM). After the site characterization stage is complete, a long-term groundwater monitoring network is established based on the DFN datasets and the SCM. This system is then monitored at appropriate locations, depths and frequency over long periods of time to continue testing the SCM and provide confirmation of SCM predictions or early warning of unexpected impacts.

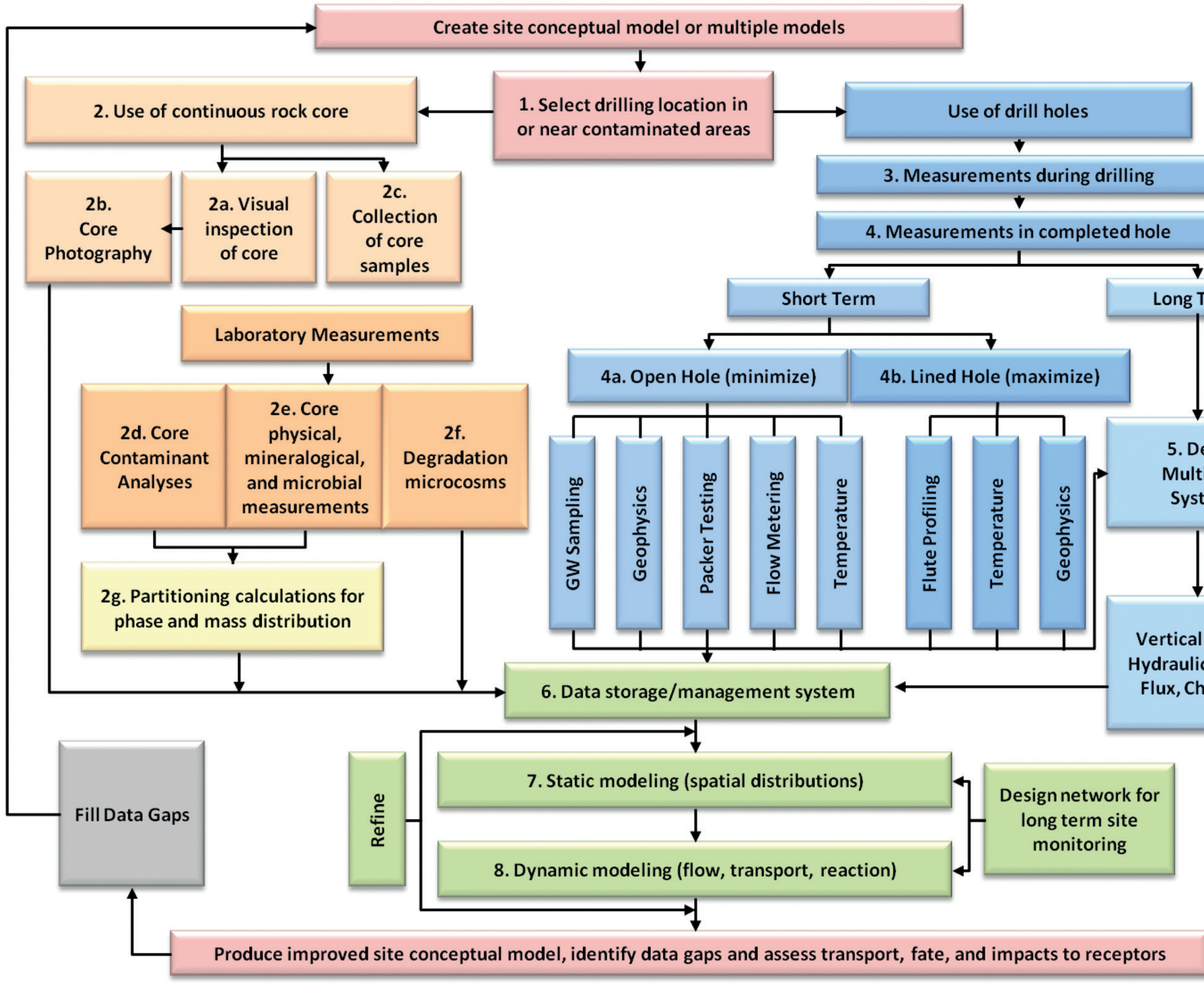

Fig. 2*: (The DFN approach uses both rock core and core hole derived dataset to characterize contaminated sites on fractured sedimentary rock.*

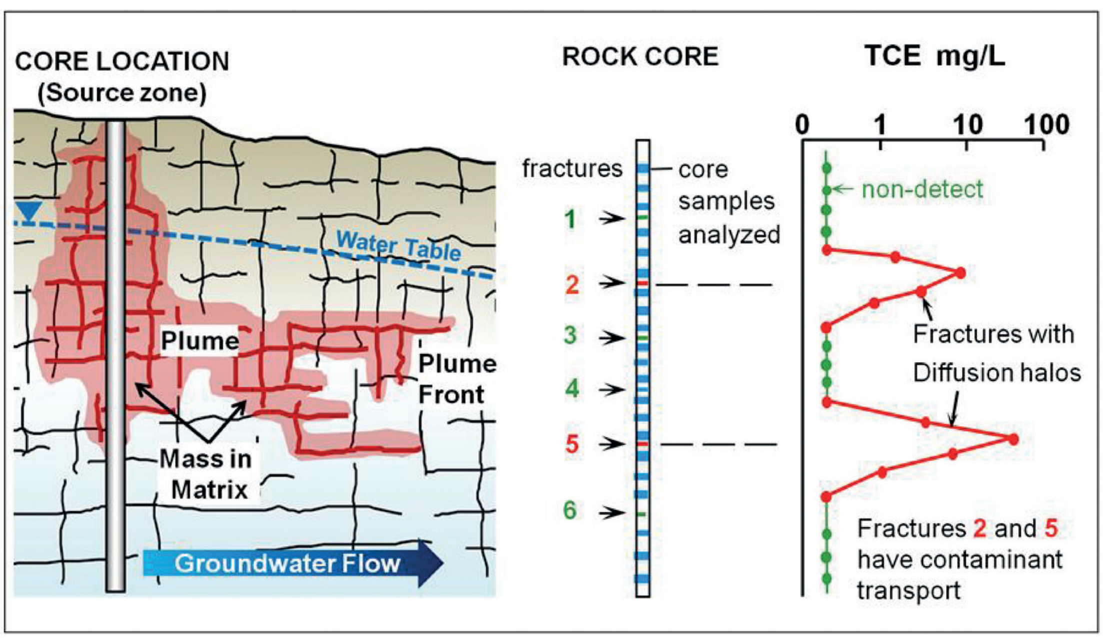

Fig. 3: *Rock core sampling approach and conceptual contaminant profile. Rock core profiles are used for identifying fractures where contaminant transport occurs and assessment of contaminant mass within the matrix..*

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Tab. 2: *Description of elements in the DFN approach following the flow chart (Figure 2). Minimization of the open hole methods refers to the need to minimize the time the hole is left open after drilling to reduce borehole cross connection and cross contamination.*

A Discrete Fracture network Approach (DFN) for Investigation of Contaminated Sites on Fractured Sedimentary Rock			
1	Drill continuous cored hole in or near area of suspected contamination, but not through zones of suspected free-phase DNAPL		
2	Use continuous rock core to determine contaminant mass distribution in rock, fracture spacing/orientation and matrix properties of the core relevant to contaminant mass storage and behaviour		
3	Measurements during drilling for insights about hydraulic head distributions and permeable zones		
4	Measurements in the completed hole to determine formation characteristic and groundwater flow		
	Activity	**Purpose**	**Description**
2a/b	Visual core inspection/ core photography	Geology/Fracture Identification	Texture, structures, minerals, bedding, fractures, coatings
2c	Core sampling	Lab analysis	Samples crushed/field preserved in methanol
2d	Contaminant analysis	Mass distributions	Crushed sample microwave extraction and VOC analysis of methanol extract
2e	Core properties	Understand behavior in matrix	Lab measurements of porosity, permeability, mineralogy, f_{oc}
2f	Core microbiology	Understand behavior in rock matrix	Microbe identification/characterization; microcosm degradation experiments
2g	Partitioning Calculations	Determine distribution in porewater and solids.	Use K_{oc}-f_{oc} based sorption estimates
4a Open Hole	Groundwater sampling	Understand cross contamination	Use discrete depth point sampler in the open water column
	Geophysics	Formation and fracture properties	Gamma, EM conductivity, image logs (ATV, OTV), Caliper
	Packer testing	Hydraulic conductivity	Up to four types of tests for good accuracy
	Flow metering	Cross connection assessment	Metering of vertical flow; heat pulse, EM or mechanical methods
	Temperature profiling	Cross connection assessment	High precision temperature measurements in flowing water column
4b FLUTe Lined Hole	Liner profiling	Measure K and T profiles	Profiles measured from rate of descent as the liner goes down the hole
	Temperature profiling	Identify hydraulically active fractures	High resolution temperature profiling in the static water column in lined hole with and without heating the water column
	Borehole geophysics	Formation rock properties and geology	Geophysical logging inside lined hole: gamma, EM conductivity, neutron, resistivity logging, etc.
5	Multilevel systems (MLS)	Obtain head profiles, water chemistry	Select commercially available MLS: Westbay, FLUTe, Waterloo-Solinst, CMT. Design positions of monitoring intervals and seals based on core and borehole data
6	Data storage system	Organize and store all data in a relational system	Organize QA/C, store all data in a relational database system, queryable to facilitate data interpretation
7	Static modeling	Display borehole data to facilitate interpretation	Use software such as WellCAD (1-D profiles) and ViewLog (1-D and 2-D) and PETREL (3-D) for log interpretation and spatial modeling
8	Dynamic Modeling	Simulate groundwater flow and contaminant transport	Simulate 3-D groundwater flow using FEFLOW or MODFLOW based on EPM assumption and DFN simulations of flow, transport and fate in 2-D using FRACTRAN, HydroGeoSphere

Role of Surface Observations

At some investigation sites, there is sufficient exposed bedrock for surface geologic observations to be useful or evidence of regional fracture (e.g. fault) systems that are visible at surface. For example, mapping of fractures and faults within the context of the surface geology can provide insightful information. Fracture length information cannot be obtained from boreholes but can at some sites be obtained from rock surface exposures examined on the ground and using aerial photography and satellite imagery. Therefore, at sites where rock outcrops exist, information from these outcrops is incorporated into the DFN approach. The other avenue for surface observations is surface measurements using geophysics. An exploration into the use of surface geophysical methods within the context of the DFN approach is in the early stage with the expectation that use of advanced surface geophysical methods may provide useful insights, primarily at sites where overburden covers the bedrock surface and at sites where the distribution of faults or other major structural features may need to be explored. Use of surface geophysics in the traditional role, to provide improved understanding of the bedrock surface and major structural features is well established however modern equipment and data inversion methods continues to advance capabilities. The value of surface geophysics for providing new insights concerning the nature and density of fractures in rock needs to be subjected to further research.

Rock Core Contaminant Analyses

he first step in the application of the DFN Approach at aged contaminated sites is to drill continuously cored holes and take numerous, closely spaced samples from the core for laboratory analysis of contaminant concentrations and physical and chemical properties after detailed visual inspection and logging of rock and fracture characteristics (Figure 3). Use of this method to determine fractures where contaminant transport occurs, and contaminant mass and phase distributions, is essential rather than only relying on data from monitoring wells to determine contaminant nature and extent. Monitoring wells or multilevel monitoring systems are generally not effective for comprehensive site characterization because they only sample groundwater from the fractures and not the rock matrix where nearly all contaminant mass resides. Also, samples from monitoring wells are prone to the influence of cross contamination due to open hole conditions or long well screens. Rock core contaminant analyses are done on small sections of rock collected along the entire length/depth of the core with an average 0.3 m spacing resulting in high resolution determination of the contaminant mass distributions. This average spacing is typical for sedimentary rock, such as sandstone, limestone and dolostone, where the primary contaminants have minimal sorption. The deepest hole where this method has been applied is 450 m. At sites where contaminant diffusion into the matrix is expected to be more limited, due to shorter times since the contaminants entered the systems or given matrix properties such as lower porosity or more sorption, sample spacing is more focused near fractures. Each contaminant category (e.g. volatiles, semi-volatiles, non-volatiles, metals) requires specific procedures for sampling, preservation, processing, and analysis. The rock core chemical analyses provide total contaminant mass and these are converted via calculation into dissolved and sorbed fractions as appropriate. Rock core samples are also retained for physical (e.g. porosity, permeability, diffusion coefficient), geochemical (e.g., mineralogy, organic carbon content) and microbial characterization. For sedimentary rock, the analysis typically shows nearly all contaminant mass occurs in the low permeability rock matrix as a result of diffusion from the fractures into the matrix over years or decades. The typical small rock matrix permeability limits disturbance of contamination in the matrix during drilling; however the extent of DNAPL must be considered and incorporated into drilling plans to prevent possible cross-connection and downward mobilization. Most of the studied sites have evolved to non-DNAPL conditions so that there are no rock core concentrations are above or close to solubility. Therefore, under these conditions downward mobilization of DNAPL is no longer an issue and holes are drilled through former DNAPL zones (Parker et al., 1994, 1997). Although the core hole is used for complementary methods to further understanding of groundwater flow and contaminant distribution after the core has been removed, it is the rock core contaminant results in the DFN Approach which guide application of these other methods. The field and laboratory procedures for collecting and analyzing rock core contaminant concentrations have been transferred to the commercial sector (referred to as the CORE DFN™ Approach).

Impermeable Flexible Liner (FLUTe™) Technologies

In the contaminated zone, the next step in the DFN approach immediately after drilling the hole is complete is creation of a borehole seal using a flexible impervious liner. Several methods in the DFN Approach involve removable ‘flexible liners’, referred to as FLUTe™ technologies. Collaborations have been ongoing with the developer of these technologies since 1997 to test, demonstrate and extend their unique capabilities for investigations in fractured rock. A ‘liner’ is an impervious fabric ‘sleeve’ installed in boreholes by eversion with water, such that the sleeve ‘lines’ the hole forming 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 the hole to exit from other fractures. In areas where groundwater contamination exists in the bedrock, this cross-connecting flow causes chemical cross-contamination that confuses monitoring well data interpretation and commonly alters the pre-drilling contaminant distribution (Sterling et al., 2005). 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, have a monitoring system installed, or be permanently sealed with grout. The FLUTe™ liner is the only practical method now available to quickly but temporarily seal a hole. Initially FLUTe™ liners were installed in holes solely to seal the hole against cross-contamination; however two other advantages have since been developed; measurement of borehole hydraulic conductivity (K) and transmissivity (T) as the liner is installed (Keller et al., 2011) and high resolution temperature measurement in the static water column inside the liner (Pehme et al., 2010) as described below.

High Resolution Temperature Logging

High resolution temperature profiles measured in the static water column inside the borehole sealed with a FLUTe™ liner provide identifications of fractures with flow under ambient groundwater conditions. In traditional logging in unlined boreholes, cross-connection effects cause the temperature results in the unlined hole to misrepresent the ambient groundwater system (Figure 4). In this approach, once disturbance of the groundwater system caused by drilling and the open hole flow dissipates, which usually takes a few days, the temperature profile in the water-filled, lined hole shows many frac-

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tures with active groundwater flow without influence of the borehole (i.e. ambient conditions) as shown in Figure 4 comparing results from temperature logging in the same borehole under open and lined conditions (from Pehme et al., 2010). In hydraulically 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 an advanced temperature probe which resolves to better than 0.001°C. Typically temperature profiles in lined holes under ambient conditions show the perturbation deep into the rock of transient temperature variations imposed at ground surface from the atmosphere or subsurface urban infrastructure. The temperature profiles show the disequilibrium of the thermal regime caused by groundwater heat transport. Typically, temperature profiling in lined holes identifies many more hydraulically active fractures than in holes without a liner (Pehme et al., 2010). The use of temperature profiling for identification of hydraulically active fractures has been enhanced by the Active Line Source (ALS) technique (Pehme et al., 2007; 2012) in which the entire static water column inside the liner is heated and then the heat dissipation monitored by repeated profiling over several hours. This substantially increases the sensitivity and depth range for fracture identification. An ALS temperature profile taken at a dolostone site in 2010 is included as part of the composite dataset shown in Figure 5.

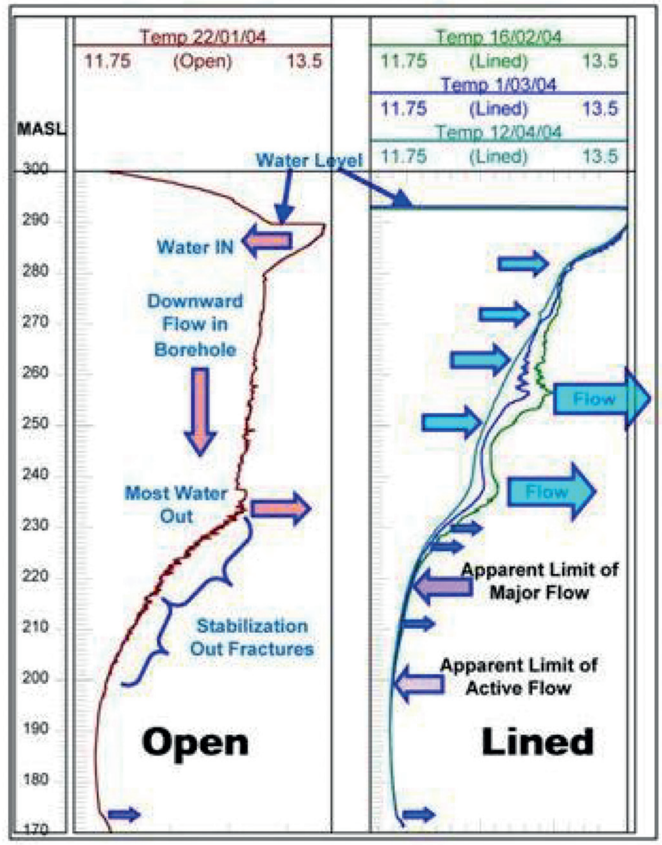

Fig. 4: *Comparison of interpretations of temperature logs collected in open and lined borehole at the Cambridge site (Table 1); blue arrows indicate major and minor flow zones (from Pehme et al. 2010). In the open hole, downward flow originating from shallow fracture(s) near the water table dominates the upper part of the temperature profile, and this vertical cross-connected flow masks flow zones identified in the lined hole representing ambient conditions. This shows how logging in open holes produces a misleading interpretation of natural flow conditions. The lined-hole temperature logs show many more flow zones and also a very different interpretation of the relative amounts of water movement in the zones that are identified or in some cases masked by vertical flow in the open hole.*

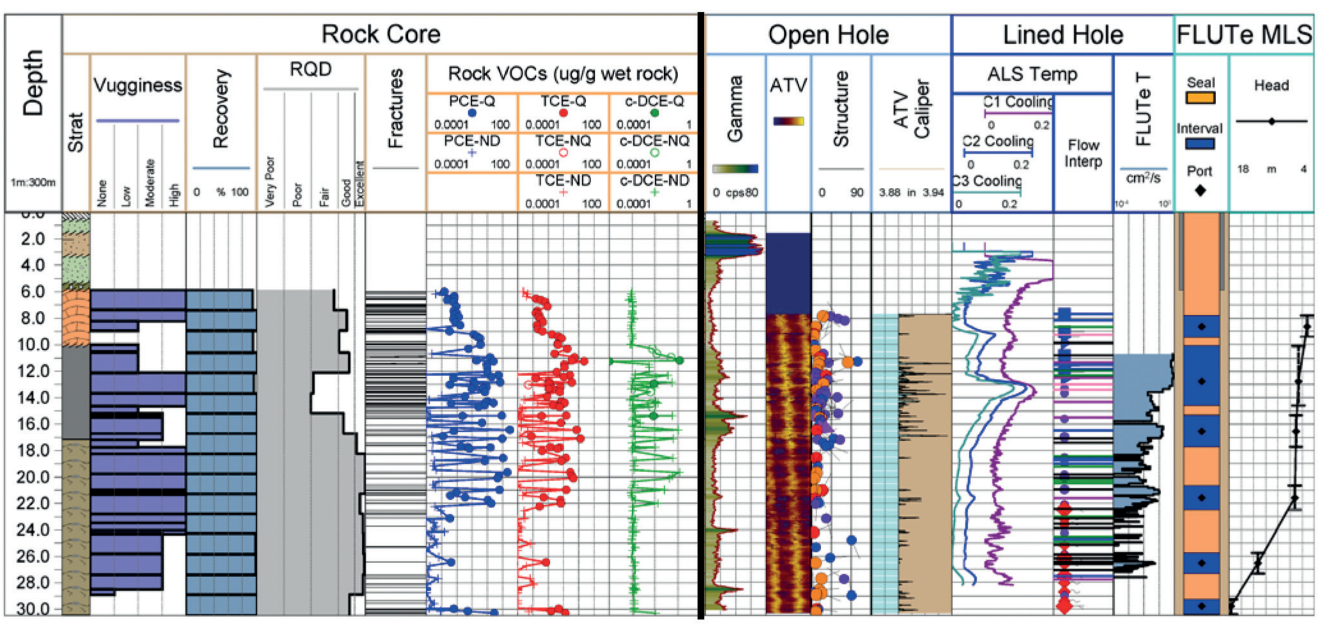

Fig. 5: *Example prepared using WellCAD of a portion of a composite DFN data set from rock core and borehole measurements and a MLS at a contaminated dolostone site in Guelph, Ontario (Table 1).*

Improved Hydraulic Tests Using Straddle Packers

Determination of the hydraulic nature of the borehole described primarily by the bulk transmissivity (T) of the entire borehole and depth-discrete transmissivity (T) along the length of the borehole are important components of DFN investigations. In the conventional approach for investigation of fractured rock, where groundwater flow rather than contaminant transport is the emphasis, packer tests carried out by the drillers in a few intervals in the hole are typically used to obtain 'order-of-magnitude' values for the transmissivity of the test interval. In research investigations the packer tests were sometimes done using a single test method along the entire borehole length using a fixed test interval such as one meter. However, in the DFN approach, where the focus is on determination of the hydraulic apertures, the goal is to obtain the most accurate values possible within the constraints of reasonable effort and cost. Hydraulic conductivity (K) or transmissivity (T) profiles along the holes are used to calculate Cubic Law based hydraulic apertures (2b), needed as inputs to DFN models. Depth discrete T values are derived from multiple hydraulic tests and aperture values are determined using the cubic law in which the hydraulic aperture is proportional to [T/N], where N is the number of permeable fractures in a test interval. In the DFN Approach, two types of hydraulic tests are used to obtain T profiles: (i) hydraulic tests using straddle packers set with small test intervals (~1-2 m), and (ii) FLUTe liner profiling. These two types of tests are used synergistically; liner profiling provides depth discrete T values for the entire length of borehole, and comprehensive packer testing is used to refine or confirm these T values for representative and/or anomalous intervals. The intervals of the borehole designated as a priority for packer testing are identified by core inspection, borehole logs and FLUTe™ profiling results. While hydraulic tests in boreholes using packers have existed for a long time, the DFN Approach uses advanced equipment and procedures for improved accuracy and precision because groundwater velocity is very sensitive to aperture and apertures and flow conditions are sensitive to induced stresses (Quinn et al, 2011a; 2011b). Quinn et al. (2012) describes packer testing equipment and approaches in more detail. In these tests, rubber packers with sleeves are used for improved seals to isolate an interval of the borehole and a suite of hydraulic tests are conducted including constant head step tests, rising and falling head slug tests, pumping tests and recovery tests to ensure tests conducted within the linear flow range. This comprehensive suite of hydraulic tests is conducted to obtain the best possible T values for calculating hydraulic apertures for velocity estimates with minimum error and uncertainty. To obtain hydraulic apertures using the cubic law, an estimate of the number of permeable fractures present in each test interval is required. 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 for all of the fractures in the test interval. A range of fractures present in each test interval is first determined from all available data. (e.g. image, core and temperature logs). However, it is unlikely that all of the fractures identified by these methods are hydraulically active. A method has been developed to use the onset of non-Darcian flow in constant head step tests to aid in the selection of the number of hydraulically active fractures in each test interval (Quinn et. al., 2011b). This procedure results in a statistical spatial representation of the properties of the fracture network, which are then used in static and later in dynamic DFN modeling.

Conventional Borehole Geophysics

Conventional borehole geophysics also plays a role in the DFN approach. The geophysical logs that are considered to be most important are gamma, electrical resistivity and EM conductivity, which provide insights concerning the geology at the hole, and digital image logs, either acoustic or optical televiewer or at some sites both are used. The image logs are used primarily to identify fractures and their orientation and obtain a virtual caliper measurement (from the acoustic image log) which is used in the packer test planning and for assessing fracture frequency along with other lines of evidence. The above mentioned borehole geophysical methods all obtain information about the formation rather than about the nature of the water column in the hole. Conventional borehole geophysical methods such as fluid resistivity, flow metering and standard temperature logging are used only occasionally in the DFN approach because their value is minimal relative to the new borehole data acquisition methods such as high resolution temperature profiling inside lined holes. Also, these conventional geophysical methods are done in open holes and one of the objectives in the DFN approach is to minimize the time that the hole is open allowing hydraulic cross contamination. In the preferred scenario, the open hole geophysical logging is done immediately after drilling of the hole or most commonly at a later time when the liner is removed for a short period of time specifically to allow for the geophysical logging and in some cases the straddle packer hydraulic tests are conducted during this brief open-hole time interval. Some conventional geophysical logging can be done without diminished resolution inside the lined hole (e.g. gamma, neutron and apparent conductivity). Data from these conventional approaches are also combined with measurements made in the DFN approach such as physical property measurements for characterization of formation properties (e.g. porosity and bulk density). These conventional geophysical techniques can also be useful within the DFN approach for improving interpolations between boreholes and extrapolating away from the detailed investigation locations for plume scale and regional site conceptual model development that involves the static and dynamic modeling described below. The DFN coreholes serve as 'keys' that can be used to interpret the standard geophysical logs run in many regional and site holes. Without DFN coreholes serving as 'keys' the regional holes would be difficult or impossible to incorporate into the models.

Other Data Acquisition Methods in Open Holes

In the DFN Approach, there is emphasis on minimizing the time that the hole drilled for site characterization is allowed to be open because of the desire to minimize cross contamination effects. Sterling et al. (2005) describe an example of an open hole study of TCE cross contamination in fractured sandstone, showing strong effects even after only a short cross-connection period of a few days. However, a common circumstance at contaminated industrial sites is the presence of old monitoring wells with long open hole intervals, that have existed for many years or even decades. Commonly, these open intervals are between 5 and 20 or more meters in length and often not placed with knowledge of contaminant or hydrologic unit boundaries. Given that in sedimentary rock hydraulically active fractures typically occur at spacing of tens of cm or less, open hole intervals of only several to a few tens of meters may be cause for concern pertaining to vertical cross contamination between fractures and distinct hydrologic or contaminant zones. Therefore, there is need to assess the effects of such cross contamination by examining the conditions of vertical flow and hydrochemistry in the hole.

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This is most efficiently done by using a combination of several types of borehole measurements, most importantly borehole flow metering (heat pulse, EM or spinner) with and without pumping (e.g. Paillet, 2000) high resolution temperature profiling (Pehme et al., 2010) and passive water sampling (no pumps) at several depths. This type of sampling can be done using the Snap Sampler (Britt et al., 2010) diffusion sampler or a canister sampler. Although it is undesirable to allow open holes in contaminated areas to remain open longer than is essential for collecting critical data, there is usually the possibility in contaminated site investigations to conduct open hole studies at locations close to but beyond the contamination. We have found this detailed work in ‹clean› holes to be useful at some sites, particularly for conducting open hole geophysical logging and straddle packer testing to a degree much beyond what is recommended in contaminated areas.

Multilevel Monitoring Systems

The DFN Approach uses depth-discrete multilevel systems (MLS), sometimes along with conventional monitoring wells, to obtain hydraulic head and hydrochemistry profiles. A 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. Because nearly all flow occurs in the fractures relative to the rock matrix, the data from the MLSs are considered to represent conditions in the fractures only. Specifically, MLSs are designed to collect temporal information on hydraulic head and water chemistry, both natural and contaminant. 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. Four different types of MLSs are available from commercial suppliers: Water FLUTe™ from Flexible Liner Underground Technologies, the Waterloo and CMT® Systems from Solinst® Canada Ltd., and the Westbay® system from Schlumberger Canada Ltd. Each system offers a variety of design and equipment options. Choosing a MLS depends on site specific hydrogeologic conditions and monitoring objectives, with clarity for the selection provided by the complementary DFN Approach data sets. Once the type is chosen, the MLS is custom designed for each hole by specifying the lengths and positions of monitoring intervals and sealed segments based on data sets collected as part of the DFN Approach. Commercially-available MLSs can accommodate from 6 to approximately 40 monitoring intervals in a 150 m deep, 10-cm diameter borehole. In conventional practice, MLSs are typically designed with only a few monitoring intervals compared to the maximum number possible for each type of system. In the context of the DFN Approach, MLSs are designed to maximize the number of monitoring intervals to provide the most detailed data possible and to avoid cross-connection of different aquifer and aquitard units. This desire for many monitoring intervals is based on experience showing that the critical intervals where detailed head profiles are needed cannot in general be predicted in advance (e.g. Meyer et al., 2008; 2012). For the MLS to provide hydrochemistry representative of in situ conditions, sufficient time must pass after installation to allow cross-contamination effects to dissipate, which may take many months or even years. 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.

Data Storage and Management

The DFN Approach generates highly resolved spatial and temporal data from multiple sources requiring a data management system with exceptionally large data storage capacity and the capability to explore relationships between the various datasets to produce integrated interpretations. Existing software for data storage and management were found to be inadequate; therefore, a relational database system was developed specifically for datasets collected using the DFN Approach. This database system improves efficiency and consistency in data collection, facilitates QA/QC procedures during all stages of data acquisition and management, and assists in data interpretation. Furthermore, this database system ensures the DFN data is comprehensively archived, which is critical given the volume of the data collected, effort and expense in collecting the various datasets, and the time required to fully capitalize on the data from a scientific standpoint given the long-term nature of these sites and problems. Use of the database system starts in the field at the drill site to ensure the coring data being collected are consistent and of the highest possible quality. The core is photographed, described and sampled following a framework designed to capture all data required by the DFN Approach, expose errors and omissions, force consistency between logging personnel and minimize bias. User input and experience is used to continually update and streamline the database system. The data base system easily interfaces with or outputs data for use in data display and static modeling (described later) software such as WellCAD, Viewlog and Petrel. The focus on data storage and management within the DFN approach is due, in part, to the recognition that large numerical models of groundwater flow and contaminant transport are prone to diminished credibility if the modeling process is not traceable and transparent. The terms traceable and transparent imply qualified persons external to, and independent of, the project are able to retrieve all site data used to construct the model, inform important decisions, and assess assumptions in a convenient manner. Ultimately, if desired, such persons should be able to run the models to assess conclusions based on model outputs. This level of transparency and traceability is not possible without a comprehensive data management system.

Example DFN Field Datase

The DFN Approach was applied in Fall 2010 to six boreholes in Silurian Dolostone at a site in Guelph, Ontario contaminated with PCE, TCE, and their daughter products. Figure 5 shows a comprehensive DFN data set collected at one location from this site. The left panel focuses on data collected from the continuous rock core including geologic data sets (stratigraphy, vugginess, fractures) and rock core contaminant profiles. The very closely spaced rock core contaminant analyses show nearly all of the mass is between 10 and 22 mbgs and the mass is not limited to or consistently distributed within a distinct stratigraphic unit. There was no reason to suspect this contaminant distribution from the general hydrogeological circumstances, and therefore, close sample spacing along the entire core was essential. The right panel shows data sets collected from the corehole. Data collected both from the core and the corehole provide multiple lines of evidence for a dense fracture network. Fractures identified from the continuous core and acoustic televiewer show many fractures but cannot differentiate between fractures with active groundwater flow and those without. The datasets collected from the FLUTe lined hole include active line source (ALS) temperature logging and a FLUTe transmissivity profile. These datasets are directed at identifying transmissive fractures and fractures with active groundwater flow and indicate the presence of many active fractures. All of the DFN datasets were used to design a MLS targeting zones of flow/ high contaminant concentrations without cross-connecting different hydrogeologic units. The MLS is used to collect head profiles and provide groundwater samples for a wide range of hydrogeochemical and contaminant analyses. The head profile shows three distinct segments: a small change in head with depth in the upper portion, a flat section of minimal vertical gradient in the middle portion, and a large change in head with depth in the lower portion of the hole. The flat portion of the head profile suggests a dominance of horizontal flow and a dense network of interconnected fractures. The sharp change in head with depth is likely indicative of an aquitard unit. An additional five coreholes were completed, four to 30 m and one to 72 m depth extending into the shale aquitard, with comprehensive data sets obtained at each. These six coreholes provide the basis for a detailed SCM and decisions about future investigations.

Modeling

Two general types of modeling are conducted as part of the DFN approach: (1) static and (2) dynamic modeling. Emphasis on static modeling (i.e. 3-D spatial) to represent geology and assist in delineation of hydrogeologic units and nature and extent of contaminants as examples is an important step prior to dynamic flow and transport modeling. In the preferred approach to static and dynamic modeling, these modeling efforts are begun early in the site investigation process so that the models are tools ‘to organize thinking’ and ‘to guide data collection (Bredehoeft, 2010). Each type of modeling is described in more detail below.

Static Modeling

The main objectives of static modeling is to interpolate and extrapolate the information between boreholes so that the models for groundwater flow and transport are based on the best possible three dimensional representations of the geology, physical hydrogeology and contaminant distributions. Static modeling is aimed at formalizing the development of these spatial distributions using advanced software referred to as static models. The initial step in static modeling is comprehensive interpretation of all of the various types of data sets on a hole by hole basis. The foundation for use of DFN data in static models is the compilation, QA/QC, storage, and management of borehole data in the relational database system. The data management system is essential to the appropriate and efficient display of DFN data. For this one-dimensional step, various software are used, culminating in the use of WellCAD for data integration and display (e.g. Figure 5). For the extension of the interpretations into three dimensional space, Petrel or similar software becomes the primary tool. At the rudimentary level, these extensions are based primarily on basic statistical considerations; however, ultimately there is need to make more formal use of geologic origins of the geologic units and geomechanical considerations for the fracture networks. In conventional approaches for groundwater flow and transport modeling, the step between assembling the borehole data, borehole by borehole, is typically informal based on simple algorithms and personal judgment. An objective in the DFN approach is to expand and formalize this step to take advantage of methods developed primarily in the petroleum industry and to better inform or translate these methods to shallower, freshwater systems.

Dynamic Modeling

Dynamic numerical models advanced to simulate flow and transport in the 1990s included complexity of fracture networks and processes for interactions between fractures and matrix. However, computing power was quite restrictive and, most importantly, no sufficiently detailed field studies of existing contaminant plumes were available to parameterize or ground truth these models. The purpose of applying the DFN Approach for field site characterization is to develop reliable site conceptual models (SCMs) and related mathematical models to serve as the framework for decisions concerning long term monitoring, remediation, and site management. Dynamic models for groundwater flow and contaminant transport are used to represent the present state of contaminant distributions, make future predictions of transport and fate, and evaluate remediation alternatives and efficacy. However, models for flow and transport are only as good as the SCMs on which they are based; therefore, the development of the SCM is the most important step in the overall modeling process requiring integration of conceptual models for geology, hydrogeology, and hydrogeochemistry. The ultimate goal of mathematical modeling is simulation of contaminant transport and fate. This modeling must be done using DFN transport models in which processes in both the fractures (advection and dispersion) and the rock matrix blocks between fractures (diffusion, sorption, and reactions) are adequately represented. Although 3-D numerical DFN models for contaminant transport exist (e.g. HydroGeoSphere, FEFLOW), none has shown to be capable of representing fractured rock domains large enough to encompass actual plumes at the field scale. Therefore, a practical approach at present is to apply 2-D DFN transport models (e.g. FRACTRAN) to represent plume evolution and predict future plume behavior with hydraulic boundary conditions and groundwater flux constrained with calibrated 3-D EPM groundwater flow models (e.g. Chapman and Parker, 2011). Output from DFN simulations can be compared stylistically with field data collected using the DFN Approach, such as rock core VOC profiles and head and concentration data from MLS. The 2-D DFN models are recognized as simplifications of reality because they are 2-D and the statistical generation of fracture networks cannot capture the full complexity and heterogeneity of actual fracture networks and thus deterministic simulations are not a goal. However, when sufficient characterization data have been collected to define reasonable input parameters, DFN simulations can provide valuable insights into controls on contaminant attenuation caused by diffusion and other processes. Thus a goal is apply DFN models which incorporate relevant processes and their interplay in both the fractures and matrix for stylistic representation of field conditions, and also adequately represent plume attenuation caused by diffusion and other processes.

Figure 6 shows results of 2-D DFN simulations tailored to an intensively studied plume at the California site. Darcy flux along the plume flowpath was obtained from a 3-D FEFLOW model constructed for the site. The mean matrix porosity of the sandstone at this site is about 13%. The dense fracture network (Figure 6a) has lognormal fracture apertures with mean of 100 microns and variable lengths (Figure 6b). The average linear groundwater velocity in the fracture network can be estimated using: , where K_b is the bulk hydraulic conductivity (derived from the flow simulation), i is the average hydraulic gradient and f_f is bulk fracture porosity (provided as model output based on the generated fracture network), which assumes all flow occurs through the interconnected fracture network. With imposed hydraulic gradients of 1% horizontal and 0.5% verti-

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cal (downward), the average linear groundwater velocity is about 7 m/day for this scenario. Simulated groundwater velocities in some fractures are much higher than this average value with a maximum of about 30 m/day (Figure 6c), indicating potential for rapid plume migration in the absence of diffusion and other processes. Simulation results show rates of plume migration are much slower even without degradation (Figure 6d, LHS), with the plume front less than 800 m downgradient after 50 years, and peak concentrations are significantly attenuated with distance. Incorporation of even very slow rates of contaminant degradation can have a substantial impact on plume attenuation (Figure 6d, RHS). Such low degradation rates, whether via biotic or abiotic processes, are too low to be measured in laboratory studies over practical time periods. Rates of degradation in the rock matrix of significance in fractured rock settings are much slower than typical rates reported for microcosm and field studies in unconsolidated sediments for chlorinated solvents (e.g. Wiedemeier et al., 1999). Degradation in the matrix, besides causing direct contaminant loss, also has the effect of enhancing diffusion since higher concentration gradients are maintained driving diffusion into the matrix.

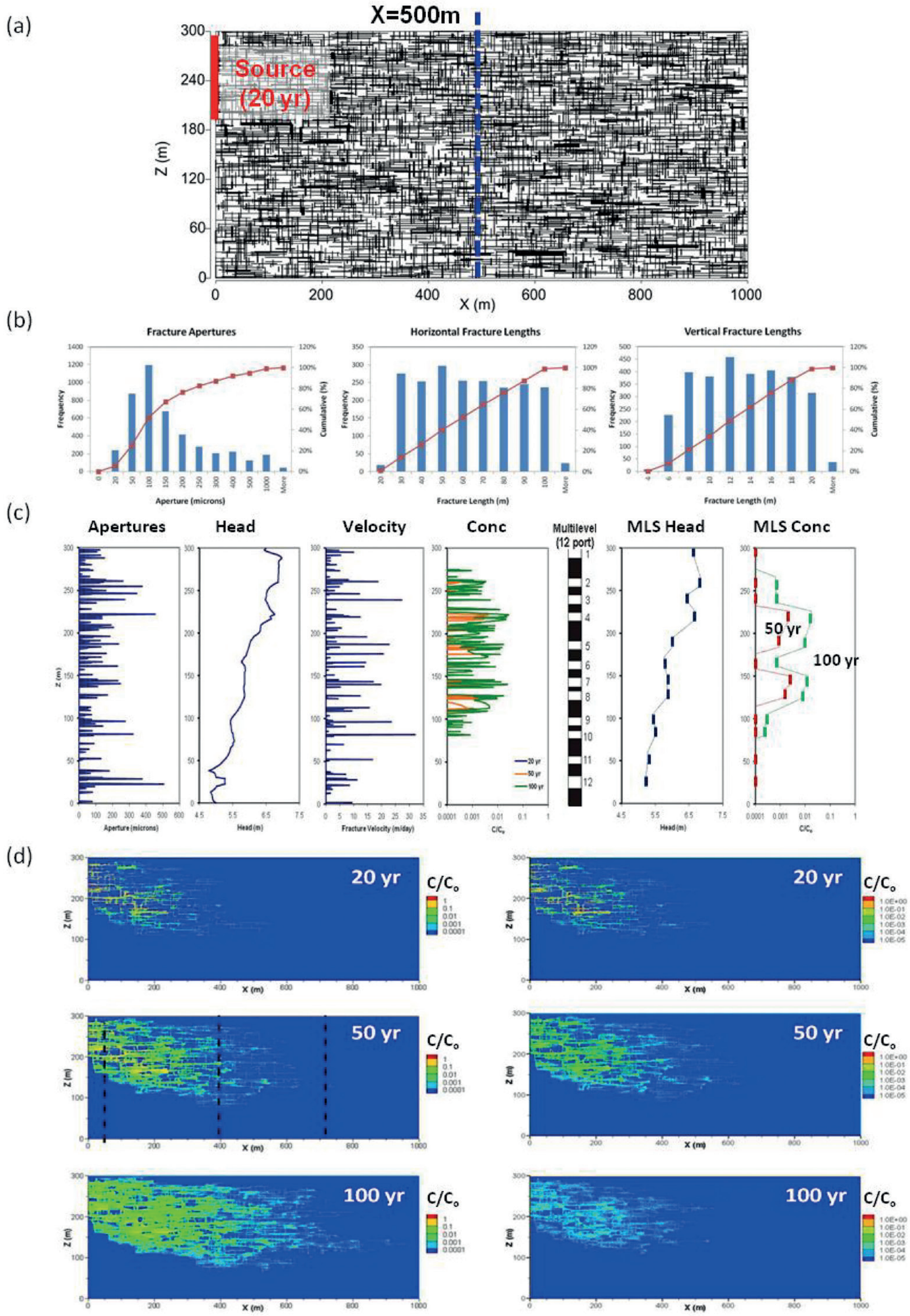

Fig. 6: *Example FRACTRAN DFN simulation tailored to California site: (a) fracture network, (b) aperture and length distributions, (c) profiles showing fracture apertures and simulated head, fracture flow velocities and concentrations at x=500 m and head and concentrations for a hypothetical MLS, and (d) simulated TCE plume at 20, 50, and 100 years for scenarios with no degradation (LHS) and with slow degradation (10-yr half-life).*

Figure 7 shows a comparison of simulated versus field conditions for a plume at the California site. The plume was delineated using two transects and a longsect along the plume flowpath (Figure 7b). The depth-discrete rock core total equivalent TCE porewater concentrations along the plume longsect were depth-averaged over 6 m intervals to represent bulk scale plume conditions. Simulation results are from the scenario shown in Figure 6 without degradation, with results taken at 60 years, which is consistent with elapsed time between when initial releases occurred at the site and the field data were collected. The FRACTRAN DFN simulation results reasonably represent maximum and depth-averaged field concentrations along the longsect (Figure 7c). Also the bulk plume characteristics (Figure 7d) are also reasonably represented by the model (Figure 7e). This provides good confidence that this approach, combining 2-D DFN models for contaminant transport with flow constraints from 3-D EPM flow simulations, using site specific parameters, can produce simulated plume conditions that show excellent representation of plume style and contaminant distributions and the magnitude of plume attenuation. DFN simulations can also be used for exploring remediation efficacy (e.g. Parker et al., 2010). Similar application and comparisons with field data is underway at several of the detailed study sites.

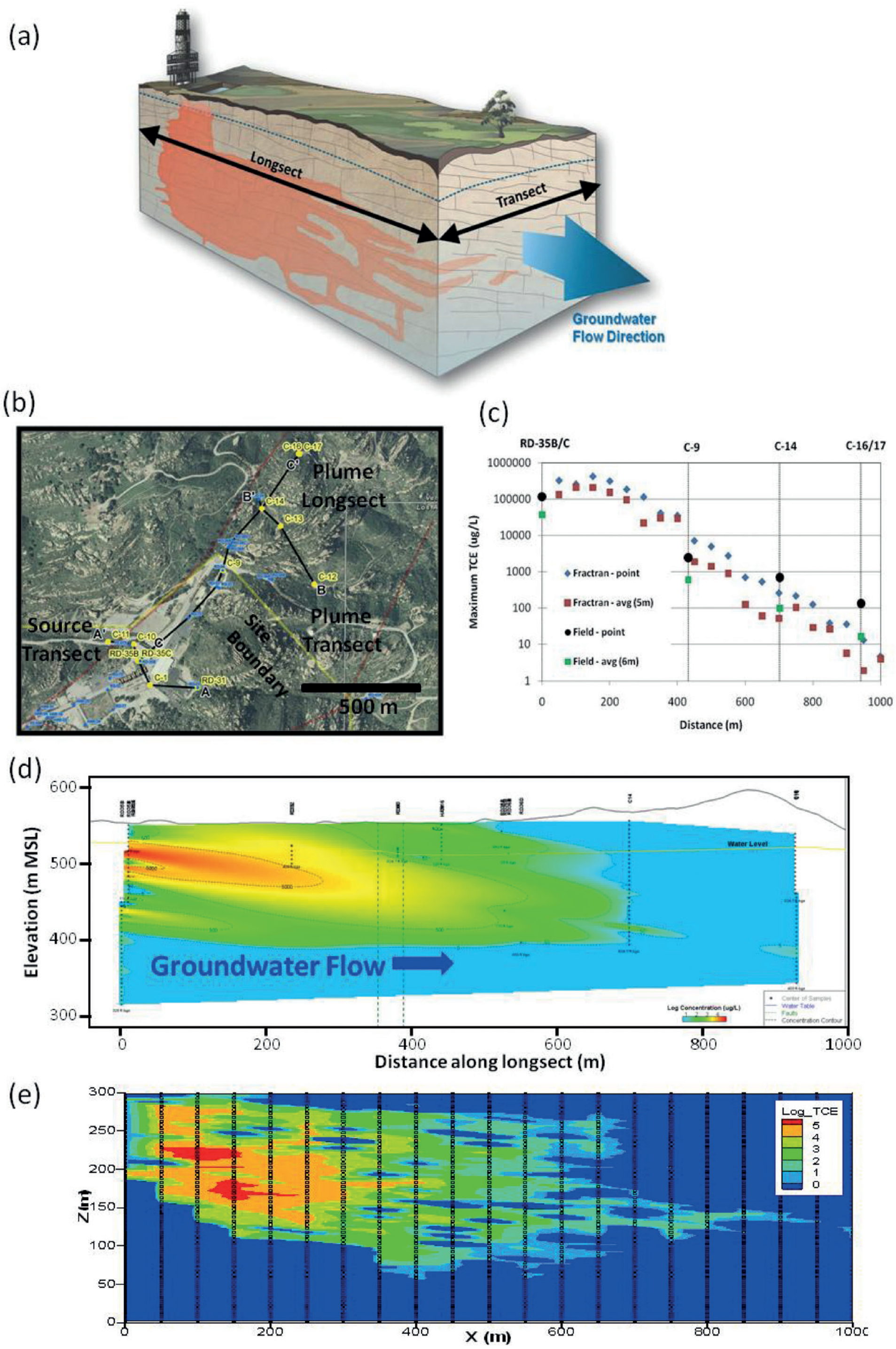

Fig. 7: *Longsect comparison between FRACTRAN 2-D DFN simulation tailored to a plume at the California site and field delineated plume via rock core sampling: (a) schematic and use of transects and longsect, (b) plan map of field site with plume delineated along two transects (source area A-A' and plume area B-B') and along a longsect C-C', (c) comparison of field versus simulated maximum equivalent TCE versus distance along longsect, and comparison of (d) field versus (e) simulated depth averaged TCE along longsect.*

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Summary of Key Findings

The application of the DFN approach at the eight intensive study sites (Table 1) has resulted in several general conclusions concerning fracture networks, contaminant distributions and transport and fate processes common to all of the sites. The contaminant distributions at these sites developed over decades essentially represent long term natural gradient tracer experiments. The details of the rock core profiles provide insight regarding fracture spacing in which transport occurs. Prior to the initiation of these contaminated site studies using the DFN approach, there was concern that complexities in the geologic structures and fracture network characteristics would cause the subsurface source zones and plumes to be extremely difficult or practically impossible to locate and delineate. However this has not turned out to be the case for any of the eight sites. The fractures in which active groundwater flow occurs are numerous, generally closely spaced and well connected, which has resulted in the contaminant plumes being orderly and monitorable, rather than being chaotic or disorderly and not amenable to reliable monitoring (Figure 8). The characterizable behavior of contaminants at these sites is attributed to the strong interplay between the matrix and fractures due to dense, interconnected fracture networks.

Hydraulic apertures are typically in the range of 50-500 microns and the average linear groundwater velocity (Darcy flux divided by the bulk effective fracture porosity) is generally a few to tens of meters per day. While average linear groundwater velocities in fractured sedimentary rock are relatively large, matrix diffusion has caused the contaminant plumes at the eight sites to be very small relative to expectations based on such velocities. This strong plume-front retardation in fractured sedimentary rock is primarily a result of matrix diffusion causing contaminant transfer from groundwater in fractures to the low permeability rock matrix, as well as contaminant storage in the matrix due to sorption. Matrix diffusion has such a strong influence on plume behavior because in this ground-truthed SCM contaminant transport occurs in a well-interconnected fracture network with closely spaced fractures where there is large surface area for diffusive mass transfer.

At seven of the eight sites, the initial DNAPL mass has mostly or entirely transformed into dissolved and sorbed mass in the rock matrix. Thus, there is no difference in the state (phase and distribution) of the contaminant mass between the former DNAPL source zones and the plumes, consistent with expectations for DNAPL disappearance by dissolution and diffusion (Parker et al., 1994; 1997). At such "aged" sites contaminants continue to diffuse into the matrix blocks in some zones while outward diffusion back into the fractures occurs in other zones. Such slow back diffusion causes contaminants to persist in former DNAPL source zones for extended periods (decades to centuries or longer) despite complete dissolution of the original DNAPL phase. The implication to remediation of contaminant mass residing primarily in the matrix is that the return of groundwater to drinking water standards requires removal of essentially all of the matrix mass (Parker et al., 2010). However the evolution of the source zone to a non-DNAPL condition causes reduced contaminant mass loading over time, which results in maximum concentrations in the plumes also diminishing over time. Microbial degradation products of chlorinated solvents have been found at most of the

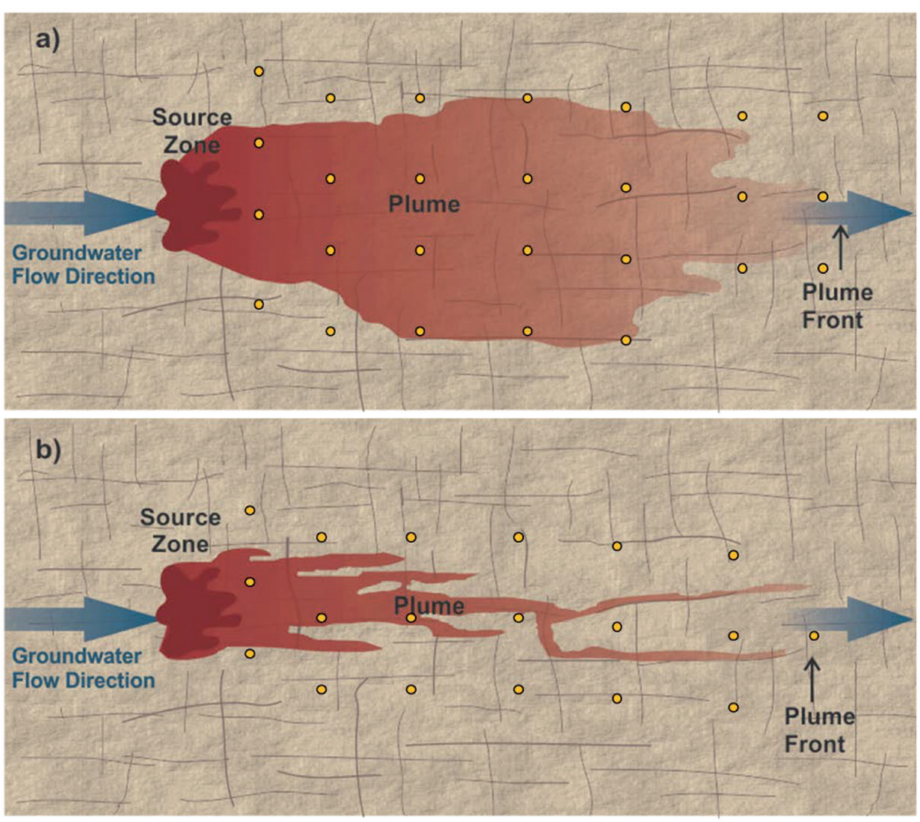

Fig. 8: *Two conceptual plumes caused by DNAPL entry into fractured rock: (a) monitorable plume due to strong transverse dispersion and spreading in well interconnected fracture network, and (b) alternative model with plume funneling into a small number of major fractures making monitoring difficult.*

sites, indicating that parent chemicals have undergone some degree of mass reduction due to degradation, with evidence that much of this degradation occurs in the rock matrix. Strong transverse spreading in the fracture networks and, in some cases, degradation has contributed to plume attenuation that has produced nearly stationary plumes in these sedimentary rock sites. The many methods utilized by the DFN Approach to establish fracture occurrence and frequency provide substantial confidence in conclusions concerning the occurrence of ubiquitous, well connected fractures that give rise to the orderly, monitorable, nearly stationary plumes observed at the eight intensively studied sites due to the combination of processes operating in the fractures and the matrix.

Directions of Current Research

Although the DFN Approach for investigating contaminated sites on sedimentary rock has now reached a stage sufficiently advanced for comprehensive application at many sites, several elements are the focus of collaborative research aimed at improvements; some of the topics of the current research are indicated here. Confidence in the understanding of the fracture network characteristics can be strengthened through assessment of distribution and transport of other components of the system, and therefore effort is directed at investigations of natural isotopes such as atmospheric tritium as natural tracers and at simulations of heat transport to better understand the ambient temperature distributions. High resolution temperature profiling methods inside lined holes are being extended, aimed at determining groundwater flux, velocity and flow direction. Tools are being developed independent of temperature to identify individual fractures with active groundwater flow and to measure the fluxes of groundwater and contaminants in these individual fractures. In collaboration with the companies that manufacture MLSs, design modifications are being explored and tested to improve effectiveness and versatility. At some bedrock sites, the contaminant plumes extend towards locations such as hill slopes, rivers or estuaries where access by standard rock drilling rigs is too expensive, difficult or impossible without causing excessive terrain or ecological damage. Therefore monitoring systems are being developed to install in small diameter (<8 cm or 3 inches) holes drilled using small portable machines widely used in remote terrain by the mineral exploration industry. The field components of the DFN approach are primarily suited for application in holes that are between four and seven inches in diameter. The four inch minimum diameter cores come from the common practice of drilling PQ and HQ sized core holes. In the mining industry, NQ size holes (nominal 3 inch diameter) are most common and therefore to extend the application range of the DFN approach, adaptations are in progress for 3 inch holes. Another reason to adapt the DFN approach for 3 inch holes is to extend the reach of the approach to locations that cannot be accessed by conventional PQ and HQ coring drill rigs, which are typically truck or track mounted and require a large space not suitable for all drill site conditions (e.g. steep slopes and remote areas). For this extended application of the DFN approach, some of the downhole tools and multilevel devices need to be redesigned or adapted. Field trials for several different types of these portable drilling machines are underway.

The use of static models such as Petrel and Fracman is in the early stage for integrating all forms of site data, interpolating between investigation locations and developing comprehensive interpretations. Although there are many different software packages available for manipulating, displaying and modeling site data, the diversity of the DFN data sets and the immense size of these sets have proven to be an obstacle to efficient comprehensive interpretations. Therefore, better interfaces are needed between the software packages. Concerning borehole geophysics, there is a need to know more about the resolution obtainable from various tools when used inside FLUTe lined holes. Advanced borehole geophysical methods developed in the petroleum industry for improved identification of fractures, fracture and rock matrix properties are being assessed.

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