Fractured Rock: State of the Science and Measuring Success in Remediation

September 2005

National Ground Water Association
N.E.Kinner[1], R. W. Masters[2], L.B. Fournier[3]
[1]Bedrock Bioremediation Center, University of New Hampshire
[2]National Ground Water Association
[3]STAR Environmental, Inc.

Introduction

While the decades since the 1970's have produced a steady series of advances in the characterization and remediation of contamination in porous media environments, there has not been concomitant progress on similar problems in fractured rock. Characterization and remediation of contaminated fractured rock sites is hampered by the complex geology, often including combinations of lithology; the substantial depths of unconsolidated media that often must be negotiated before reaching the bedrock; the heterogeneous fracture distribution and orientation; logistical and financial issues (e.g., difficulty and cost of drilling/coring rock vs. unconsolidated media); and the problems of contaminants and fluid movement in fracture networks and rock matrices. Interest in the field of contaminated fractured bedrock began to result in websites, conferences and workshops in the late 1990's. At that time, USEPA started its fractured rock website (http://clu-in.org/fracrock) which summarizes what is occurring at contaminated fractured rock sites with respect to site characterization and remediation. USEPA sponsored a fractured rock workshop in Providence, RI in November 2000 that identified issues concerning characterization and remediation. As a follow-up to that workshop, USEPA, the Ontario Ministry of the Environment, USDOE, Queens University and the Smithville (Ontario, Canada) Phase IV Bedrock Remediation Program convened the Fractured Rock 2001 Conference in Toronto, Canada in March 2001 attended by over 400 individuals representing government agencies, the private sector, and academic institutions.

Steimle (2002) summarized the state of practice in characterization and remediation of fractured rock as a result of the 2000 and 2001 events and a questionnaire of participants, drawing several conclusions.

- Strategies specific for remediating fractured rock, distinct from porous media, were emerging.
- There was a lack of technology/information transfer from researchers to practitioners.
- New techniques to better characterize hydraulic properties at fractured rock sites needed to be developed.

- Conceptual models of fractured rock sites needed to be developed and continually refined/updated as new data was received.

- The cost-effectiveness of obtaining core during drilling was much debated.

- Geophysical, hydraulic and chemical characterization methods were being developed and/or applied to help understand the fate and transport of contamination at fractured rock sites (e.g., borehole imaging techniques, discrete interval borehole samplers).

- Remediation consisted primarily of hydraulic capture/containment (pump and treat), with some use of fracturing to improve recovery and vacuum extraction.

Steimle also reported that an advisory group was formed to discuss research and technology transfer needs for fractured rock. The five research ideas generated were:

1. "The need to better understand the factors affecting mass transfer of contamination from fractures to the matrix and from the matrix to the fractures (i.e., matrix diffusion and counterdiffusion) in fractured rock aquifers."

2. "The necessity to conduct field studies to assess how the concepts of discrete fracture network and dual-porosity medium or equivalent porous medium may be applied."

3. "The appropriate methods for aquifer test analysis for fracture flow systems should be developed."

4. "Assess the applicability of currently used models developed for porous media for fractured systems, especially in which the geometric characteristics of the fractures are unknown."

5. "Conduct studies (i.e., fracture trace, geophysics, structural) that should precede monitoring or test well locating."

The group also gave six examples of technology transfer concepts that would be useful:

1. "Guidelines for applying porous media flow and transport models to fractured rock settings."

2. "Documented case studies (including lessons learned) comparing whole-well (no packers, purging, low flow sampling) and individual-zone sampling results (packers-in-place, diffusion multilevel samplers, or a FLUTe system) and their influence on the interpretation of the magnitude and vertical extent of contamination."

3. “Documented case studies on the use of geophysical techniques and vertical chemical profiling.”

4. “Identify the appropriate level of lateral and vertical detail needed to characterize (delineate contamination, determine risk), remediate (design, construct, operate), and monitor (remedial performance, compliance) contamination at fractured rock sites.”

5. “Identify recommended borehole methods to characterize the vertical distribution of contaminants, while minimizing cross contamination and/or short-circuiting within the monitoring well.”

6. “Establish guidelines for the use of tracers to evaluate flow and transport of field site dimensions.”

In September 2004, USEPA teamed with the National Ground Water Association (NGWA) to convene another fractured rock conference, this time in Portland, ME, where the goal was to “identify the current state of remediating contaminated ground water in fractured rock settings and make future remediation efforts more effective.” The major themes of the conference were the state of science with respect to geological, geophysical, geochemical and hydraulic characterization of fractured rock sites; use of conceptual models; numerical modeling; and remediation technologies. Panel and group discussions and workshops were held regarding the application of technical impracticability (TI) at fractured rock sites, performance assessment to measure the success of remediation technologies, and strategies for monitoring performances of DNAPL source zone remedies.

The 2004 conference was attended by 610 individuals representing the regulatory, private and academic sectors. Over 140 oral and poster presentations were made and 10 plenary speakers highlighted the state of knowledge in contaminant transport; scale issues; the interface between geophysics and hydrology; application from the petroleum industry; blast fracturing; monitoring and tracer techniques; and innovations in hydraulic containment. While 10 nations were represented, the participation was dominated by those from North America, especially the U.S.

Objectives

The objective of this paper is to summarize the results of the 2004 conference with respect to what has been learned about fractured rock in the intervening years since 2000-2001 and what the future holds. This is not an exhaustive review of the information presented at the conference, but rather a summary of highlights and trends with examples of supporting papers.

Specifically, this paper seeks to provide perspective on the following questions:

1. How has the understanding of fundamental processes in fractured rock environments changed?

2. Are the tools available for fractured rock site characterization adequate to understand flow and contaminant distribution and transport in all types of fractured rock and at the scale necessary to make remedial decisions? Is the information routinely obtained with currently available site characterization methods adequate to evaluate the ability of remedial action alternatives to achieve clean up objectives at fractured rock sites?

3. Are there limitations specific to fractured rock environments, which preclude using technologies proven in porous media?

4. Is the extent to which contaminants can be reduced in fractured rock sites with existing technologies adequate? Are strict remedial action objectives equivalent to soil and ground water MCLs used for porous media achievable with current technologies in fractured rock environments?

5. Are existing monitoring methods adequate to determine whether remedial action objectives are being met?

6. What should the research priorities be with respect to fractured rock?

<u>Caveats</u>

<u>Karst</u>

Though the conference was not limited to presentations on specific types of bedrock, there was a lack of information on karst (only one paper was specifically devoted to this topic (White et al.)). In certain areas of the U.S. (e.g., the southeastern states), contaminated karstic environments are prevalent and pose formidable challenges for characterization and remediation because of the variety of interconnections that can exist from very small (m) fractures to large (m) cavities caused by dissolution of the rock.

<u>LNAPL</u>

Most of the fractured rock sites discussed were contaminated by chlorinated organic compounds and DNAPLs (e.g., chlorinated solvents, PCBs) with only a few papers devoted to LNAPLs and methyl tertiary butyl ether (MTBE) (e.g., Hardisty et al., Burke et al.). This is not a new trend and is related to the fact that DNAPLs continue to sink in ground water traveling through overlaying media and into the bedrock. Conversely, LNAPL is usually confined to the upper regions of the subsurface. Recent evidence in the northeastern U.S. suggests that because of its high solubility and mobility in ground water, MTBE may be more of a problem in fractured rock than other constituents of gasoline.

Fundamental Processes in Fractured Rock Environments

Pickering Emulsions

Kueper et al., in an invited talk, presented data on the mechanism by which stable oil/water emulsions are formed for NAPLs in the presence of finely divided solids (e.g., iron, magnesium and manganese oxides, bentonite clay). These Pickering emulsions can form when mixing energy is added (e.g., drilling through a NAPL zone using muds). The concern is that Pickering emulsions provide a mechanism for NAPLs to migrate through large fractures in bedrock. Pickering emulsions may account for cases where NAPL concentrations *in situ* are: higher than solubility predicts, spike after drilling, or exist beyond distances predicted by models of adverse-dispersive transport.

Matrix Diffusion

At the 2004 conference, matrix diffusion of contaminants into rock, which is a function of rock porosity, degradation constants and fracture spacing, continued to be a topic of discussion and case studies and conceptual models were described where it accounted for a significant percentage of the contaminant mass (e.g., Vitolens et al., Guswa et al., West and Kueper). This concept was highlighted by Shapiro at the 2001 conference and may account for back diffusion (release of contaminants) into ground water during remediation. Sterling et al. showed that transfer of contaminants from ground water to the rock matrix can cause severe cross contamination within a borehole in sedimentary rock. Parker described a core analysis method for fractured sedimentary rock that can be used to identify diffusion halos from fractured rock matrices and also can help locate major contaminant migration pathways. Many conceptual and numerical models still only address dissolved phase contamination, even in rock formations with potentially significant porosity, suggesting that the concept of matrix diffusion needs to be more effectively communicated to practitioners, especially with the advent of core analysis protocols which can be useful in quantification of this process.

Fracture Surfaces

A new trend in bedrock research is the examination of fracture skins or weathering rinds (i.e., the rock surfaces immediately adjacent to the ground water flowing in a fracture). These surfaces appear to be colorized by adherent microbes that may play a role in the geochemistry within the fractures, particularly in small (micro) fractures (Eighmy et al.) and in solute transport (Garner and Sharp). The geochemical distribution of major and minor ions determined by methods such as Piper diagrams) and stable isotopes (e.g., ^{18}O and ^{2}H) may be used to demonstrate hydraulic containment (e.g., Sayko et al.), quantify abiotic degradation pathways (Cho et al.), or assess hydraulic parameters such as recharge (Fass and Reichert, Walsh, Stutts). While these types of analyses require highly trained geochemists and may be expensive, they offer another "tool" which can provide useful input for conceptual models. In addition, these analyses may only have to be done once and on select samples to provide sufficient supporting evidence to existing models developed from more traditional methods (e.g., borehole geophysics).

Tracers

Becker gave an invited talk on the use of non-reactive tracers in fractured rock to provide information on molecular diffusion, hydrodynamic dispersion and heterogeneous advection. Tracers can include fluorescent dyes (e.g., Jeffers and Wittig), stable isotopes, bromide, and microspheres, the latter as analogs for colloids and microbes. Ledoux et al. provided one of many case studies where tracers were used to aid in the development of conceptual models at a fractured rock site. Use of tracers has increased since the 2001 conference and may provide a tool that can answer specific questions with regard to a conceptual model for a site (e.g., the relative importance of diffusion, dispersion and advection).

Tools for Site Characterization

The goal of site characterization is to understand ground water flow and contaminant distribution and transport in fractured rock at a scale sufficient to make remedial decisions. The majority of the presentations at the conference focused on site characterization tools and issues, including most of the invited talks. Geological, geophysical and hydrologic tools, drilling methods, and conceptual and numerical models were the subject of talks and posters and examples of their use in several case studies were presented. Information was presented at both the regional and discrete fracture scale.

Geologic Tools

Traditional geologic tools (e.g., photolineament analysis, fracture spacing and orientation at outcrops, inventories of mapped faults and fracture networks, and Rose diagrams are used primarily for regional scale information (Thompson et al.) and where an inexpensive approach is needed (e.g., Leonardo and Jorge, Guagnelli and Koolik). At individual fractured rock sites, this information may be too gross for making remedial decisions, but may provide evidence for conceptual models and initial impact for siting boreholes and developing an overall site characterization. No new methods were reported at the 2004 conference with respect to structural geology.

Geophysical Tools

In 2000-2001, the usefulness of several geophysical methods was discussed in an effort to provide tools to practitioners for site characterization. Several surface geophysical tools (e.g., seismic reflection/refraction, electrical resistivity, ground penetrating radar, magnetotelluric surveys) were reported in several papers as a cost-effective means to determine where to locate initial boreholes (e.g., Murray and Vest). A suite of borehole geophysical tools (e.g., temperature and conductivity logs, natural gamma and caliper logs, borehole radar, tomography, optical and acoustic televiewer) are commonly being used in fractured rock, with particular emphasis on borehole flowmeter as one of the most useful (Johnson et al., LeBourge et al.). Two new borehole tools were introduced at the 2004 conference: a drilling parameter recorder (DPR) that gives real-time information about the formation during drilling (Sadkowski et al.) and a water depth, pH, temperature, ORP, conductivity and dissolved oxygen meter that can identify fractures that contribute to ground water flow. Conger and Low presented one of several case studies where geophysical data was used to help describe the hydrogeologic framework.

Drilling

Aguilera, and Finney et al. discussed the utility of directional drilling at various angles to obtain information from fractured rock. To date, this technique has not been used very much at contaminated sites, yet most oil and gas exploration wells in fractured rock are directional. Directional drilling can be useful in obtaining samples or creating wells in inaccessible places (e.g., under buildings and wetlands), for pump and treat or blast fracturing applications. It is a promising technology whose applications are evolving. With respect to traditional vertical drilling and core collection, the approach of using small rock samples to determine matrix diffusion (i.e., Parker) is also very promising. For remediation and assessment, the choice of drilling method can be crucial to the success of the project. If fractures are vertically-oriented, a vertical well will only intercept a few fractures so that site assessment information obtained from the bore is extremely limited and the deployment of the remediation technology suffers from a small radius-of-influence. When vertical fractures are present, a better choice is the use of directional-drilling for both site characterization and remediation activities. The horizontal well will intercept far more fractures, typically, than will a vertical well, especially if the fractures are poorly inter-connected and vertically-oriented.

Carlisle reported on the successful use of a vertical/horizontal well couplet to recover gasoline in fractured rock.

Hydrologic Tools

Traditional methods of hydrologic analysis were presented in many papers and posters using data from packer, slug and pumping tests to estimate hydraulic conductivity, transmissivity and fracture connectivity (e.g., Hale, Pulidio et al., Cho et al.) however, mot of the reports were not based on new technology, but rather modifications of existing methods or new ways to assist in data analysis (Enachescu et al.).

Integration of Geophysical and Hydrologic Tools and the Importance of Scale

Paillet, in an invited talk, noted that the "successful characterization of aquifers at the site scale requires the effective integration of the three basic tools at our disposal: (1) surface geophysical soundings provide full non-destructive coverage of the aquifer volume, but are generally ambiguous in interpretation and fail to identify individual fracture conduits; (2) geophysical measurements in boreholes can characterize fractures in detail, but only adjacent to individual boreholes; and (3) hydraulic measurements in boreholes can be used to generate direct relationships between geophysical and hydraulic properties for the rock immediately adjacent to the borehole." His presentation, along with that of Shapiro, examined the key issue of choosing the appropriate scale for site characterization. Shapiro emphasized how synthesis of many types of data (i.e., lab; field; ground water flow; distribution of dissolved, gaseous and isotopic constituents; modeling) may be necessary to fully understand and address issues of scale.

There were several studies where geophysical and hydrologic data were used to characterize sites, in some cases in conjunction with tracers and discrete fracture chemical sampling. These data were the basis of conceptual models or mass-flux approaches (e.g., Green et al., Eby et al., Pearson and Murphy, Fiacco et al.). Doe et al. discussed how such an approach was used at the Aspö Hard Rock Laboratory in Sweden at various scales to understand solute transport in fracture networks. Together papers demonstrate how such a unified and multi-faceted approach to characterization has evolved to become more standard practice at fractured rock sites.

One question that arose during the panel discussions was the frequency with which such an integrated approach is used. Some panelists observed, whether because of the lack of technology transfer, interdisciplinary teaming or financial resources, combinations of tools are not always used. Thus results in inadequate site characterization, incorrect choice of scale and poorly-informed remedial decisions.

Mathematical Modeling

As was the case in 2000-2001, several papers were presented on the development and use of numerical models to characterize fracture networks, contaminant transport and ground water flow at small and regional scales (e.g., Wang and Earle, Kenny et al., Wiezel et al, Fitts, He and Thalheimer, Dershowitz et al.). Most of these were developed specifically for fractured media and were not adapted from existing porous media models. While many of these models were somewhat successful for their application at specific sites, panel discussions concluded that even models used to characterize porous media are not that good, so successful applications in fractured rock is likely to be more difficult, if not impossible. Two issues that Steimle (2002) recommended be addressed remain unresolved three years later: there is no "unified federal approach to research and development concerning modeling" and "there are no guidelines for applying porous media flow and transport models to fractured rock settings."

Conceptual Models

Insight derived from characterization is integrated and unified in a site conceptual model. In 2000-2001, there were few examples of this approach at fractured rock sites. This is one major area where progress was clearly demonstrated at the 2004 conference. There were several presentations that served as examples of conceptual model development and refinement as new data was received (Culkun et al., Bond and Linnell, Dougherty and Soo, Michalski, Mokry et al., Lima, Harte et al., Campbell et al., Gutmann et al.) Panel discussions also highlighted the use of conceptual models as diagnostic tools that can be updated regularly using new data collected at the site for feedback on the model's validity. As in all environmental fields, conceptual models must undergo verification and validation repeatedly to insure they are representative of *in situ* conditions. In spite of this trend, there were still sites where conceptual models did not appear to be developed as part of site characterization and evaluation of potential remedial actions. This process must be codified to make it universal.

Remedial Technologies and Limitations to Their Use in Fractured Rock

In 2000-2001, Steimle (2002) noted that while more than one remedial technology was used at most fractured rock sites (n = 53 sites), 51 used pump and treat as their primary process, followed by various forms of vapor/vacuum extraction (20), *in situ* oxidation (10), monitored natural attenuation (MNA) (4), bioremediation (1) and other processes (3). [N.B., At the 53 sites, multiple technologies were used resulting in additive totals of the processes > n = 53.]

In 2004, pump and treat was still widely used to remove contaminant mass and hydraulically contain plumes. This approach can last for > 20 years (Phillips and Walters, Kalluri et al.), often with diminishing returns. Modifications of pump and treat were reported where contaminant mobilization techniques was used to help mass removal, particularly from microfractures or the rock matrix. These included steam injection (Davis et al., Parkinson and Brown), surfactant injection (Ivey and Craft), and RF heating (Brody et al.). In some cases, fracturing has been used to enhance injection or extraction (Pearsen et al., Smerekanicz et al., Blum et al.). As a result of limited data sets, small scale (pilot-test) application and short term monitoring, it is difficult to conclude the long-term effectiveness of these remedial technologies in contaminated fractured rock.

Some innovative approaches to hydraulic containment (tunnel and drain collection for PCBs (Guswa et al.) and a seepage barrier made from coal combustion products to mitigate acid mine drainage (Warner et al.)) were described, but these projects are new and little data was available on their effectiveness.

While many of the technologies used for remediation in porous media have been tried in fractured rock, the 2004 conference presentations and panel discussions indicated that *in situ* chemical oxidation (ISCO) especially with permanganate, is being tested most widely (Gefell et al., Rohde and Butler, Simons and Seinberg, Konzick et al. Blum et al., Naron et al.) almost exclusively for the chlorinated solvents PCE and TCE. In most of these cases, ISCO has proven somewhat successful at the pilot scale and various larger scale tests are being tried. Difficulties remain with the introduction and distribution of the oxidant in fractured rock and the extent of its long-term effectiveness in microfractures or with material residing in the rock matrix.

Other technologies used in porous media such as nanoscale zero-valent iron (Gheorghiu et al.), vacuum extraction (Carter and Kryczkowski) and in-well air stripping (Puck et al.) were presented, but again the data available was limited and/or only demonstrated the potential of a technology to work on the small (pilot/lab) scale.

Several papers were presented where bioremediation was selected as a remedial strategy (Chartrand et al., Rottero et al., Pearson et al., Carter and Kryczkowski, Voci et al., Durant et al.), again primarily for chlorinated organics, using bioaugmentation (injection of microbes) and/or a chemical biostimulant (e.g., methane, HRC, ethanol). While pilot scale results were encouraging, few studies used standard methods that provided multiple lines of evidence supporting bioremediation (e.g., monitoring of electron donors/acceptors, stable carbon isotope ratios). Once again the large-scale, long-term efficacy of this remedial approach remains unresolved for fractured rock.

At many sites, multiple processes are used in the remediation of contamination in fractured rock. For example, Vanderglas and Murphy described an integrated approach of source removal, expansion of an existing SVE system and bioremediation with addition of fast and slow release carbon sources to remediate a landfill impacting a limestone fractured rock and ground water system. Kalluri et al. described a sandstone site where PCE was spilled in 1994 and after initial free phase recovery and pump and treat for 10 years, the contaminant still present at concentrations of ~ 13,000 g/L. They described the process of site characterization and evaluation of potential remedial strategies, highlighting specific process limitations to attaining site closure. They concluded that continuing operation of the current containment system was most cost effective until a technology is available to treat matrix-diffused PCE and achieve ground water quality standards of 25 g/L.

Based on the papers and posters presented at the 2004 Conference, it is premature to answer the question of whether there are limitations specific to fractured rock which preclude use of proven remedial technologies used in porous media. However, some of the most daunting challenges clearly are delivery and distribution of injected materials and/or recovery of contaminants in microfractures, low flow zones and rock matrices. While these delivery/recovery problems are not unique to fractured rock, they are often more difficult to overcome in this complex medium. It is too soon to determine if the promising technologies of ISCO and/or bioremediation will prove successful on the large scale in some of the more difficult/complex fractured rock environments where contaminants are embedded in the rock matrix and in low flow zones.

Ability of Existing Remedial Technologies to Meet MCLs

The focus of much of the panel discussion at the 2004 conference centered on the ability of existing remedial technologies to meet strict cleanup standards (e.g., similar to ground water MCLs). Some remedial technologies such as ISCO appear, at least at the pilot scale, to have the ability to reduce contaminant concentrations in ground water to low g/L levels. Still outstanding is the question of whether this effect is transient and whether back diffusion of contaminants from the rock matrix or low flow zones and microfractures will cause a subsequent rebound of ground water concentrations.

In the panel discussions and subsequent polling of the Conference Advisory Council, there were divergent views about this issue. Some individuals believed that existing technologies will be shown to be sufficient to meet strict MCLs, especially when: multiple methods are used over time, areas within the contaminated site are treated by different processes, and the remedial strategy is developed using a "treatment train" approach vs. a single solution. Those who shared this view stressed that remediation will be a long-term proposition taking > 5 years in fractured rock, after immediate risks are reduced. Two key factors to this multiple technologies approach that will be essential to the ability to meet strict MCLs are: (1) using a "life cycle" approach to remediation that insures that initial processes will not inhibit/prevent the success of subsequent remedial technologies, and (2) insuring that each step in the remedial strategy protects people from exposure to contaminated drinking water or unacceptable vapors.

Other individuals countered that it is currently too daunting to attempt to remediate many fractured rock sites to meet strict MCLs, because this often requires reducing contaminant concentrations several orders of magnitude. They maintained that decisions must be made on a site-by-site basis and that setting MCLs as the goal for all but the long-term raises expectations too high. They suggested setting initial goals of reducing contaminant concentrations one to two orders of magnitude, then transitioning to more strict regulatory levels over the long-term, with the proviso that transition points are set ahead of time and performance metrics are clearly defined.

Most agreed that it was difficult to describe when remediation is "done" and a site can be closed, especially because of the potential for back diffusion of contamination from the rock matrix into the ground water. Ultimately, protection of human health and the environment is the goal and this may take a very long time to achieve and demonstrate it has been attained. At sites where there is little or no primary porosity in the rock matrix and few microfractures exist, remediation may be easier than contamination in porous media.

The factors that affect the success of remediation are: the degree of aquifer heterogeneity, the location of the contamination (i.e., low flow zones, rock matrix, ground water), the degree of site characterization, the adequacy of the site conceptual model, and the ability to deliver and extract remediation materials and contaminants, respectively, within the site. The worst case scenarios are ones where heterogeneity abounds, there is high primary porosity, a prevalence of contaminants, microfractures, little site characterization, and a poor or no conceptual model. These sites will also be difficult to monitor and the uncertainty associated with the data and remedial success will be high, even posing the possibility of increasing environmental risks if contaminants are mobilized or added (e.g., perchlorate from blast fracturing)
.

The issue of cost also cited as an integral component of site remediation. Some expressed the view that existing technologies could reduce contaminants to strict standards, but that costs of such remedial strategies in fractured rock would be extremely high, perhaps exceeding the ability of PRPs to pay, because of site complexity and the depth of contamination. Pump and treat/hydraulic containment, in spite of the long-term commitment to O&M, may offer in some cases a better (more protective and cost effective) option than more experimental remedial technologies that have high uncertainty. For example, risks such as cross contamination of fracture zones and potential for plume displacement into previously uncontaminated areas may result from non-containment strategies.

In cases where remedial technologies are not implemented, two alternatives have been instituted in fractured rock environments: monitored natural attenuation (MNA) and application of technical impracticability (TI). MNA for petroleum hydrocarbons and chlorinated solvents is a long-term scenario usually coupled with pump and treat/hydraulic containment in a suspected source area. Three papers at the conference discussing sites where MNA has been or is being considered, all cite biodegradation as the natural attenuation process for ground water and long-term back diffusion of contaminants out of microfractures and the rock matrix (Landin et al., Kinner et al., Lunderman and Lipson).

TI designations are occurring at some sites and this was the topic of a panel discussion. Two cases studies were presented as papers (Kastrinos et al., Lay et al.). In both cases, DNAPLs were present and impacted the decision to grant the TI for the fractured rock. Discussions at the conference indicated that TIs were most likely to be considered when DNAPLs were present and/or when the contamination in the fractured rock was very deep. In these cases, institutional controls such as the TI variance, deed restrictions and replacement of water supply wells were implemented at fractured rock sites allowing closure. There appeared to be some variability in the willingness of regulatory agencies to consider and/or allow TIs.

Site Monitoring

Once remedial strategies are selected, there are two key issues that must be addressed before implementation can commence: selection of monitoring methods and designation of performance assessment metrics.

Monitoring Methods

Most of the monitoring methods presented at the 2004 conference were not new. Individual uses included various borehole isolation systems (e.g., straddle packers, Westbay system, multi purpose packer systems); FLUTe™ multi level sampling liners, and low flow and passive diffusion bag samplers (Eschner and Dinsmore, Lesley and Lees, Pulido et al., Burke et al., Cherry et al.). All of these technologies appeared to be able to produce data that were representative of the *in situ* concentrations of contaminants in ground water. The issue of data usefulness was strongly linked to the use of discrete interval monitoring in boreholes vs. open borehole sampling, especially where vertical gradients exist. Discussions stressed the need to explain to PRPs the importance of using costly discrete monitoring techniques to obtain more useful data. In addition, the need for peer-reviewed data sets before, during and after technology implementation at field sites was discussed (i.e., data must meet strict quality control standards for reporting). It was noted that oftentimes site characterization is considered more important and only a small amount of resources are dedicated to this. As a result, inadequate data sets are often generated that fail to demonstrate statistically significant success at meeting performance metrics. Information collected during remediation is also sometimes not available because of the proprietary nature of the process. Tracers may be useful in normalizing results (e.g., C/C_o concentration histories normalized to those of a conservative tracer). Determination of the fate of contamination in the rock matrix may need to be verified with selective rock core sampling using a protocol similar to that described by Parker.

Performance Metrics

The topic of performance metrics was the subject of a panel discussion. The group emphasized that there cannot be a fixed set of performance metrics for fractured rock because criteria are site- and technology-specific. However, the metrics can be established including interim criteria. There should be clearly delineated and accepted prior to remediation. Flow charts should be created that include timelines and decision points. Multiple criteria (line of evidence) should be established and data quality objectives used. Most of these points are not unique to fractured rock contamination sites and should also be applied to pilot scale and other controlled experiments designed to demonstrate the potential effectiveness of a remedial technology. Mass flux monitoring, coupled with the use of conceptual and mathematical modeling, can be used to address whether a remedial strategy is failing to meet established performance metrics. The worst case scenario is that too few ground water and rock samples and very low monitoring budgets, combined with the complexities of a fractured rock environment, create a situation where neither failure nor success with respect to achieving performance metrics can be demonstrated. This situation is untenable for regulators and PRPs.

Research Priorities

Progress on Previous Priorities

As noted earlier in the paper, Steimle (2002) presented five research ideas and six technology transfer products that needed to be addressed in the future. Before setting new research goals based on the 2004 conference, an evaluation of how the 2002 priorities have been met is worthwhile.

1. The 2004 conference demonstrated that issues such as a matrix diffusion are of concern, but our basic understanding of factors such as mineral coatings, short term recharge, fracture size and flow rate is still somewhat rudimentary. Clearly, there are no general references available where practitioners can find information summarizing these and other basic properties of different rock types and how they affect plume development and remediation.

2. Some field studies on how the concepts of discrete fracture network and dual-porosity or equivalent porous media may be applied have been published in the intervening years, but in general such work has been limited as has most research activity at fractured rock sites.

3. Aquifer test analysis for fractured flow systems has received considerable attention both in the published literature and at the 2004 conference in several rock types, with the notable exception of karst.

4. Models of fractured rock systems have been developed, some based on porous media models. A unified federal agency approach on R&D for modeling has not been developed, but in spite of this a variety of models are available. Again, there is no general reference available where practitioners can find information summarizing these models and their advantages/disadvantages and appropriate application at fractured rock sites.

5. Probably the area where most success has been achieved in the intervening years is with respect to structural, fracture tracer and geophysical studies prior to monitoring and test well location. The number of presentations at the 2004 conference on site characterization methods and conceptual model development further emphasized the heightened awareness of this area.

Steimle (2002) called for case studies with respect to open borehole and discrete zone monitoring and geophysical techniques and recommendations for borehole methods to characterize vertical contaminant distribution and guidelines for the use of tracers. To a fairly significant extent, these goals have been addressed and are closer to being met than three years ago. What lags behind is more information on cross-contamination of boreholes, guidelines for model application and details on remediation and monitoring.

Research Priorities

1. Fundamental research on the role of microfractures, fracture skins and matrix diffusion in different rock types must occur to advance understanding of these processes on contaminant fate and transport and remediation.

2. Characterization, remediation and monitoring methods for karst and DNAPLs must be given some priority, as there is a paucity of research in this area.

3. Demonstration sites for new and promising technologies need to be established for various rock and contaminant types. Findings and data from the demonstrations must be carefully documented and made readily available to practitioners through technology transfer. Scale and uncertainty issues should be addressed as part of these evaluations.

4. The benefit of source area removal needs to be resolved. SERDP and ESTCP have funded research on this topic which should be available in a few years. This issue must especially be addressed with respect to DNAPL in fractured rock.

5. Successful sites with respect to site characterization and remediation must be used to validate fractured rock models.

6. There needs to be more information collected and summarized on lessons learned and applications with respect to site characterization, modeling, remediation, and monitoring. This information needs to be made available to practitioners in general available reference materials. This is particularly important with promising technologies such as directional drilling, rock core sampling, ISCO, and bioremediation in various rock and contaminant applications and may include exploration of the use of technologies such as reactive walls and funnel and gate.

7. Cost-effective methods need to be further developed to characterize flowpaths between boreholes and delineate the long-term effect of intra-borehole mixing on vertical distribution of contamination and subsequent discrete interval sampling with depth.

8. Cost-effective delivery systems for chemical and biological remediation methods need to be improved especially to high priority areas within different fractured rock environments.

9. Horizontal and directional wells have shown promise for the purpose of characterizing and remediating contaminated ground water in fractured rock as reported by, Aguilera, Finney, and Carlisle. In addition to their use as recovery wells, horizontal and directional wells may provide better contact for nutrient delivery and more efficient stimulation of aerobic microflora in the subsurface. This should be explored.

While progress has been made on characterization and remediation of contaminated fractured rock, many issues still remain unresolved, and more carefully documented case studies and field documented research are needed. It is important to emphasize the importance of geophysics and the integration of multiple characterization techniques as the remediation of fractured rock sites continues. More information exchange with the fields of subsurface petroleum exploration and mining in fractured rock would be beneficial. In addition, there must be more multidisciplinary approaches not only to research, but to practice when addressing contamination in fractured rock because of the complexity at these sites. Finally, there is a need for technology transfer, to improve the availability of information in readily available resources for practitioners and the need for a well-defined, cost-effective approach to field demonstrations of new technologies.

References

Steimle, R. 2002. The State of the Practice: Characterizing and Remediating Contaminated Groundwater at Fractured Rock Sites. *Remediation* 12(2): p 23-33

The following references are from the 2004 EPA/NGWA Fractured Rock Conference, Portland, ME:

Aguilera, R. Oil Field Techniques for Characterizing Fractured Reservoirs.

Becker, M.W. Distinguishing Advection, Dispersion, and Diffusion in Fractured Bedrock.

Blum, B.A., B.N. Stephanatos, et al. In Situ TCE Oxidation Using Potassium Permanganate in the Columnar-Jointed Preakness Basalt of New Jersey.

Bond, R.M. and Linnell, K.E. Control of fractured Bedrock Structure on the Movement of Chlorinated Volatile Organics in Bedrock and Overburden Aquifers, Newark Basin of New Jersey.

Brody, K.L., A.R. Kabir, et al. Implementing RF Heating in Fractured Bedrock to Remediate TCA DNAPL.

Burke, T.S., S.A. Czajka, et al. An Innovative Approach to Investigation of an MtBE Plume in Fractured Bedrock.

Calkin, S., P. Thompson, et al. Fractured Bedrock DNAPL/Dissolved Phase Plume Conceptual Model Development at the Eastland Woolen Mill Superfund Site, Corinna, Maine.

Campbell, L.G., S.E. Schofield, et al. Historical and Present Site Conceptual Models for a Fractured Bedrock Superfund Site in New York State.

Carter, G.L. and R. Kryczkowski. Remediation of a Clay and Fractured Rock Source Area Using Vacuum Extraction and Bioremediation.

Chartrand, M.M.G., P.L. Morrill, et al. Evidence of Biodegradation at a DNAPL Contaminated Fractured Bedrock Field Site Using Stable Carbon Isotopes.

Cherry, J.A., B.L. Parker, et al. The FLUTe Multilevel Groundwater Monitoring System Used for Study of a Contaminated Dolostone Aquifer.

Cho, H.J., R.J. Fiacco, et al. Hydrochemical Facies Analysis of 1,1,1-Trichloroethane and its Degradation Products in Fractured Bedrock.

Cho, H.J., R.J. Fiacco, et al. Pumping Test Analysis in a Fractured Crystalline Bedrock.

Conger, R.W. and D.J. Low. Analysis of Selected Geophysical Logs at North Penn Area 6 Superfund Site, Lansdale, Montgomery County, Pennsylvania.

Davis, E.L., G. Heron, et al. Steam Injection into Fractured Limestone at Loring Air Force Base.

Dershowitz, W.S., P.R. Lapointe, et al. Advances in Discrete Fracture Network Modeling.

Doe, T., J. Hermanson, et al. Fracture Network Characterization for Studies of retention Processes at the Äspö Hard Rock Laboratory.

Dougherty, J.N., A. Soo and R.M. Alvey. Evolving Conceptual Models and Monitoring Well Reconstruction in the Passaic Formation in New Jersey.

Durant N.D., E.D. Hood, et al. Enhanced Bioremediation of DNAPL in a Fractured Limestone Aquifer: Bench Test Results.

Eby, R.K., R.E. Zimmerman, et al. Hydrogeologic Investigation of VOC Contamination in Bedrock Using Mass Flux Analysis – A Case History.

Eighmy, T., J. Spear, et al. Microfracture Geochemistry as an Indicator of Terminal Electron Accepting Processes in TCE-Contaminated Bedrock.

Enachescu, C., B. Frieg, et al. A New Visual Synthesis Tool for Transient Test Data.

Eschner, T.R. and D. Dinsmore. Groundwater Sampling Method Comparison: Low-Flow and Passive Diffusion Bag Sampling Results for Volatile Organic Compounds in Fractured Metamorphic Bedrock.

Fass, T. and B. Reichert. Geochemical and Isotopic Characterization of a Local Catchment Within Crystalline Basement in Western African Benin.

Fiacco, Jr., R.J., M.H. Daly, et al. Application of the fractured Bedrock Toolbox at Multiple Sites in New England.

Finney, D., J. Hershberger, et al. Use of Angled Drilling Techniques to Characterize Fractured Crystalline Bedrock and Minimize Migration of Suspected Non-Aqueous Phase Liquids (NAPL).

Fitts, C.R. Discrete Analytic Domains: A New AEM Formulation for Modeling Anisotropy and Heterogeneity.

Garner, T.T. and J.M. Sharp Jr. Hydraulic Properties of Granitic Fracture Skins and Their Effect on Solute Transport.

Gefell, M.J., K.L. Sperry, et al. Field-Scale TCE Oxidation in Sedimentary Bedrock: $KMnO^4$ and Br^- tracer Test Results and Extended Pilot Design.

Gheorghiu, F., L. Walata, et al. Field Testing of Nanoscale Zero-Valent Iron Particle Technology for In-Situ Groundwater Treatment in Fractured Bedrock.

Green, A., J.W. Lane, Jr., et al. Combined Use of Borehole Geophysics and Packers to Site Potable Wells in a Contaminated Area in Montville, Connecticut.

Guagnelli, I.A. and S.I. Koolik. Determining Geological Structures in fractured Bedrock From the Surface for Aquifer Characterization: A Practical and Inexpensive Approach.

Guswa, J.H., J.R. Bridge, et al. An Innovative Approach for Hydraulic Containment of PCB Contamination in Fractured Bedrock.

Guswa, J.H., J.R. Bridge, et al. Investigative Techniques Used in the Development of the Site Conceptual Model.

Gutmann, M., E. Fujita, et al. Structural Characterization and Passive Remediation of NAPL in Fractured Bedrock at a Former MGP Site: Mechanicville, New York.

Hale, J.R. Fractured Rock Transmissivity Estimates from Oscillatory Slug Test Data.

Hardisty, P.E., J. Roher, et al. LNAPL Behavior in Fractured Rock: Implications for Characterization and Remediation.

Harte, P.T., J.R. Degnan, et al. Characterization of Fractured Rock to Develop Conceptual Models of Ground-Water Flow and Transport of Mercury.

He, H.Y. and A.H. Thalheimer. Groundwater Flow and Contaminant Transport Modeling of a Fractured Bedrock Aquifer with Solution Channels at a Southeastern Pennsylvania Superfund Site.

Ivey, G.A. and D.R. Craft. NAPL Removal from Fractured Bedrock Using Ivey-Sol® (SPT®) Non-Ionic Surfactants – Successful Remediation.

Jeffers, P. and V. Wittig. Fractured Bedrock Aquifer Hydrogeologic Characterization for a Bioaugmentation Pilot Study.

Johnson, C.D., J.H. Williams, et al. Importance of Flowmeter Logging for Aquifer Characterization at Contaminated Bedrock Sites.

Kalluri, V.M., K.L. Brehm, et al. Remediation of Tetrachloroethene in Fractured Sandstone – A Case Study in Initial Successes and Long-Term Technological

Barriers to Timely and Cost-Effective Closure.
Kastrinos, J.R., R.P. Standish, et al. Remedial Strategies Applied to a Fractured Bedrock Contaminated Plume at the University of Connecticut Landfill Study Area.

Kenny, G., R. Therrien, et al. Large-Scale Mass Transport Modeling in Discretely-Fractured Porous Media.

Kinner, N.E., M. Mills, et al. Effectiveness of Monitored Natural Attenuation at Predicting In Situ Biodegradation in a TCE Contaminated Metasedimentary Bedrock.

Konzuk, J.S., MacKinnon, L.K., et al. In Situ Remediation of Fractured Bedrock DNAPL Sites Using Chemical Oxidation.

Kueper, B.H., A. Roy-Perreault, et al. DNAPL Behavior in Fractured Rock – Transport Facilitated by Pickering Emulsions.

Landin, O., S. Berglund, et al. Natural Attenuation of Dissolved Petroleum Components in Fractured Crystalline Rock: Results from Field Experiments at Äspö Hard Rock Laboratory, Sweden.

Lay, D.W., M.J. Gefell, et al. Successful Application of Technical Impracticability for Achieving a Cost Effective Remedy for DNAPL in Deep Fractured Limestone/Dolostone at a Superfund Site.

LeBorgne, T., O. Bour, et al. Using a Borehole Flowmeter to Measure Transient Hydraulic Head in Multiple-Aquifer Boreholes.

Ledoux, C., R. Therrien, et al. Investigation of the Impact of Fracture Intersection on Solute Transport in Fractured Carbonate.

Leonardo, R.S. and P.M. Jorge. Determining the Average Fracture Spacing Between Fractures and Planning the Best Paths for the Wells in a Field Located in the Middle Magdalena Basin – Columbia.

Lesley, M.P. and R.E. Less. From Low-Flow Sampling to Passive Diffusion Bag Samplers: The Evolution of Volatiles Characterization in a Triassic Shale Aquifer.

Lima, A.S. Thermal Hydrosystem of Gerês Spa (Northwestern Portugal): Proposal of a Conceptual Model.

Lindeman, R. and D.S. Lipson. Monitored Natural Attenuation of Chlorinated Solvents in Fractured Bedrock as a Selected Remedy for Groundwater at a Superfund Site.

Michalski, A. Conceptual Flow Model and Groundwater Characterization Strategy for

Sedimentary Bedrock Sites.
Mokry, L.B., G. Thomas, et al. Evaluating a Conceptual Model for Distant Coal Tar Migration by Bedrock Fracture Flow.

Murray, B.S. and M.B. Vest. Multi-Method Geophysical Approach for Characterizing a Deep Fractured Bedrock Aquifer, Anniston Army Depot, Anniston, Alabama.

Navon D., A. Vitolins, et al. In Situ Chemical Oxidation Using Permanganate for Remediation of Chlorinated VOCS in a Fractured Shale Matrix.

Paillet, F.L. Geophysical Characterization of Fractured Rock Aquifers: Accounting for Scale Effects and Putting Hydrology in the Geophysics.

Parker, B.L. Utility of Rock Core for Characterizing Contamination in Fractured Sedimentary Rocks.

Parkinson, D. and N. Brown. Remediation of a Chlorinated Solvent Contaminated Site Using Steam Injection and Extraction.

Pearson, S.C., B.B. Johnson, et al. Lessons Learned Form Bedrock Blast Fracturing and Bioremediation at a Superfund Landfill.

Pearson, S. and B. Murphy. A Case Study of Traditional and Alternative Monitoring Techniques for Solvent Contamination Within Fractured Bedrock.

Phillips, I. and M.D. Walters. Bedrock: From Foe to Friend – A Case History of Investigation and Remediation in Fractured Bedrock from 1979 through 2004.

Pucke, S., M. Odah, et al. The Art in-Well Technology – An Effective and Cost-Efficient Remedy for Soils and Groundwater in Fractured Bedrock Formations.

Pulido, G. and T.P. Ballestero. Gas Injection Tests.

Pulido, G., T.P. Ballestero, et al. Multipurpose Packer System.

Race, C.D. and L. Chu. In Situ Chemical Oxidation with Sodium Permanganate in a Fractured Crystalline Bedrock Aquifer: A Case Study.

Rhode, P.D. and C.R. Butler. In Situ Chemical Oxidation of Volatile Organic Compounds in a Fractured Bedrock Aquifer.

Rottero, T., C. Walmsley, et al. Evaluating Innovative Remediation Technologies and Success of Pilot Test Performance.

Sadkowski, S.S., W.A. Bothner, et al. Fracture Characterization at a Bedrock Bioremediation Site in New Hampshire.

Sayko, S.P., W.F. Daniels, et al. Using Major Ions Data to Support the Demonstration of Hydraulic Containment in a Fractured Bedrock Aquifer.

Sernoffsky, R. and G. Robbins. Use of the In Situ, Inc. MP Troll 9000 to Locate Fractures Contributing to Ground Water Flow in Bedrock Wells.

Shapiro, A.M. Ground-Water Flow and Chemical Transport in Fractured Rock: From Cores to Kilometers.

Simons, W.F. and P.D. Steinberg. Fractured Crystalline Bedrock Ground Water Remediation of Dissolved TCE via Sodium Permanganate Solution Injection & Re-circulation.

Smerekanicz, J.R., J.J. Elsea, et al. Blast-Fractured Enhanced Permeability Remediation System at Modern Landfill, York, Pennsylvania: A Five-Year Update.

Sterling, S.N., B.L. Parker, et al. Vertical Cross Connection in a Single Borehole: A Case Study in Fractured Sandstone.

Stutts, J.L. Aqueous Chemistry of Various Hydrogeologic Units of the Fractured Bedrock Aquifer in the North Carolina Piedmont.

Thompson, P., P. Baker, et al. The Regional Bedrock Structure at Loring Air Force base, Limestone, Maine: The Unifying Model for the Study of Basewide Groundwater Contamination.

Vanderglas, B. and B. Murphy. An Integrated Approach to Contaminant Mass Removal from Vadose and Saturated Fractured Bedrock.

Vitolins, A.R., K.J. Goldstein, et al. Technical and Regulatory Challenges Resulting from VOC Matrix Diffusion in a Fractured Shale Bedrock Aquifer.

Voci, C.J., M.S. Kozar, et al. Ethanol Biostimulation and Bioaugmentation of a VOC-Impacted Carbonate Aquifer Update.

Walsh, J.F. Isotopic and Chemical Characterization of Water from Mine Pits and Wells on the Mesabi Iron Range, Northeastern Minnesota, as a Tool for Drinking Water Protection.

Wang, M. and R. Earle. An Integrated View of Groundwater Flow Characterization and Modeling in Fractured Geologic Media.

Warner, N., M. Erbe, et al. Evaluating the Performance of a Seepage Barrier Constructed With Coal Combustion Product Grout to Reduce the Loss of Ground Water Seeping into a Former Coal-Mining Shaft.

West, M. and B. Kueper. Natural Attenuation of Solute Plumes in Bedded Fractured Rock.

White, K.A., D.S. Lipson, et al. Characterizing a DNAPL Site in Karst Terrain: Implications for Remediation.

Wiezel, T.K., G.G. Violette, et al. Using Fractran fracture Flow Modeling in Tandem with Modflow to Assist in the Development of Wellfield Protection Zones for Municipal Wells in Bedrock.