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An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites

Frederick D. Day-Lewis¹, Lee D. Slater², Judy Robinson², Carole D. Johnson¹, Neil Terry², and Dale Werkema³

¹U.S. Geological Survey, Office of Groundwater, Branch of Geophysics, Storrs, Connecticut

²Rutgers University – Newark, Department of Earth and Environmental Sciences, Rutgers University, Newark, New Jersey

³U.S. Environmental Protection Agency, Office of Research and Development, 944 E. Harmon Ave., Las Vegas, Nevada

Abstract

Geophysical methods are used increasingly for characterization and monitoring at remediation sites in fractured-rock aquifers. The complex heterogeneity of fractured rock poses enormous challenges to groundwater remediation professionals, and new methods are needed to cost-effectively infer fracture and fracture-zone locations, orientations and properties, and to develop conceptual site models for flow and transport. Despite the potential of geophysical methods to “see” between boreholes, two issues have impeded the adoption of geophysical methods by remediation professionals. First, geophysical results are commonly only indirectly related to the properties of interest (e.g., permeability) to remediation professionals, and qualitative or quantitative interpretation is required to convert geophysical results to hydrogeologic information. Additional demonstration/evaluation projects are needed in the site remediation literature to fully transfer geophysical methods from research to practice. Second, geophysical methods are commonly viewed as inherently risky by remediation professionals. Although it is widely understood that a given method may or may not work at a particular site, the reasons are not always clear to end users of geophysical products. Synthetic modeling tools are used in research to assess the potential of a particular method to successfully image a target, but these tools are not widely used in industry. Here, we seek to advance the application of geophysical methods to solve problems facing remediation professionals with respect to fractured-rock aquifers. To this end, we (1) provide an overview of geophysical methods applied to characterization and monitoring of fractured-rock aquifers; (2) review case studies showcasing different geophysical methods; and (3) discuss best practices for method selection and rejection based on synthetic modeling and decision support tools.

Keywords

fractured rock; characterization; geophysics; borehole logging; technology transfer; remediation

1. Introduction

The characterization of fractured-rock aquifers and monitoring of biogeochemical conditions within them remains a major challenge facing hydrologists and groundwater remediation professionals. The large variations in hydrogeologic properties over short distances in fractured rock result in preferential pathways for fluid flow and, to an even greater degree, for chemical transport - whether solutes or non-aqueous phase liquids. Fracture-controlled, channelized transport (Tsang and Tsang, 1989) poses enormous challenges to site characterization and groundwater remediation. Traditional *in-situ* 'point scale' sampling of fractured-rock properties (e.g. permeability) and conditions (e.g. contaminant concentrations) remains primarily based on invasive drilling approaches, the recovery of samples (e.g., cores, fluids) and the installation of fluid sampling apparatus for monitoring. Such approaches bear particularly high material and labor costs in and hard-rock systems, usually leading to interpretations based on relatively few observations over large areas. Point-scale measurements are also of limited utility, as it is widely recognized that hydrogeologic processes and properties are scale-dependent (e.g., Schulze-Makuch et al., 1999), particularly in fractured rock. At environmental remediation sites, direct invasive sampling can be severely limited, for example, due to inaccessibility caused by existing infrastructure, the hazardous nature of the groundwater constituents, and/or the potential for drilling to enhance contaminant transport pathways and allow cross contamination between fractures newly connected by open boreholes.

Geophysical methods, many of which were originally developed for oil/gas and mineral exploration, offer the potential to overcome some of the limitations of *in-situ* sampling. In recent years, these methods have emerged as valuable tools for supporting investigations of the shallow subsurface and for monitoring the dynamics of hydrogeological and biogeochemical processes that occur within it (Knight, 2000; Rubin and Hubbard, 2005; Vereecken et al., 2006). Most geophysical methods are to some extent scalable, allowing investigation depths and resolution (the latter of which is usually a trade off with depth of investigation) to be user defined through appropriate configuration of sensors and sources. The majority of geophysical methods are non-invasive when applied from the ground surface, or minimally invasive when applied from boreholes. A smaller subset of boreholes would be required to characterize an equivalent volume of fractured rock using geophysical methods compared to *in-situ* sampling. A clearly recognized strength of geophysical methods is the spatial continuity of the information contained, making them attractive for interpolating spatial structures away from/between boreholes. Despite these advantages, geophysical methods are never a direct substitute for *in-situ* sampling as rarely, if ever, do geophysical measurements directly record hydrogeological or contaminant properties. Instead, the relation between measured geophysical properties and hydrogeological properties of interest must be well understood to avoid potential misinterpretation of the geophysical information. For that reason, we stress that geophysical methods alone provide no "silver bullet" with respect to unravelling the complex hydrogeology and contaminant chemistry typical of contaminated fractured-rock sites. Instead, these technologies should be strategically utilized in combination with established *in-situ* measurements. The synergistic coupling of the relative strengths of geophysical technologies and *in-situ* techniques offers

the greatest potential for advancing the understanding of hydrogeology and contaminant transformations in fractured rock systems.

There is a pressing need for effective technology-transfer activities if the full benefits of geophysical methodologies are ever going to be realized by remediation professionals working at fractured-rock sites. Compared to other industries where geophysical methods are routinely utilized (i.e., oil and gas, mineral, and geotechnical), geophysics is commonly viewed as inherently risky within the environmental industry. This perception has developed in response to geophysics being (1) applied where site conditions should have contraindicated use of geophysical methods; (2) oversold, where the chance of detecting a target was weak at best; and (3) misinterpreted, where practitioners lacked the knowledge to discriminate between the signals coming from targets, natural geologic variability, and noise. In the absence of effective technology-transfer strategies, the risks of misunderstanding the value and importance of geophysical datasets remains high, as demonstrated by numerous examples where geophysical methods have been misapplied and reported to “not work.” Technology-transfer efforts are needed to reduce the risks of unrealistic expectations being placed on the results of geophysical characterization and monitoring studies. This is particularly important at fractured-rock sites where information needs are great yet targets such as individual fractures are difficult or even impossible to detect. Site remediation professionals working at fractured-rock sites need access to an expanded knowledge base and tools to critically evaluate proposed geophysical work and the results of geophysical surveys. Such technology transfer will ultimately result in both informed use and informed rejection of geophysics in project circumstances where methods are recommended or contraindicated, respectively. Extensive cost savings will ultimately result from early rejection of potentially ineffective methods. Advancing implementation of appropriate methods given specific survey objectives at fractured-rock sites will result in more realistic expectations of geophysical information and informed interpretation of geophysical results. Technology-transfer efforts on the application of geophysics to contaminated fractured-rock aquifers would ultimately eliminate many of the problems contributing to the mixed reputation of geophysics in the environmental community. The likelihood of successful geophysical field implementations would increase dramatically if, prior to field investigations, site remediation professionals could make better informed decisions about the likely worth and return of geophysical techniques for a specific application at a particular fractured-rock site. Strategies to achieve these objectives are reviewed and discussed in this paper.

2. Challenges in fractured rock

Fractured-rock aquifers present unique challenges for evaluation and monitoring of contaminant transport and contaminant degradation (NRC, 1996, 2000; Neuman, 2005). Dual-porosity and dual-permeability behavior is common in fractured rock, with flow and transport constrained to connected, discrete fractures that provide the permeable framework of the aquifer and preferentially channelize advective transport of contaminants. Typically, flow and transport are highly anisotropic, with directions that can depend more on interconnectivity and fracture strike than the direction of hydraulic gradients. Consequently, the characterization and monitoring of contaminant transport and natural or stimulated

biodegradation of contaminants in fractured-rock aquifers is a daunting technological problem. In particular, non-aqueous phase liquids (NAPL) and aqueous or sorbed-phase volatile organic compounds (VOCs) are long-term, persistent contamination problems (Leeson and Stroo, 2011; Parker et al., 2010, 2012). Various formulations of mobile/immobile or dual-porosity models (e.g., van Genuchten and Wierenga, 1976; Haggerty and Gorelick, 1995) are used in fractured rock to explain persistent contamination and anomalous transport behavior (e.g., Carrera et al., 1998; Zhang et al., 2006). At most ‘aged’ sites where contaminant releases occurred decades ago, recalcitrant contaminant mass now resides in the much lower permeability matrix blocks between fractures (immobile porosity) (fig. 1). Fluid samples taken from wells primarily represent the mobile porosity of the fracture networks and, therefore, often fail to accurately quantify contaminant mass, which can persist in the immobile porosity (fig. 2). For similar reasons, remedial technologies involving injections of fluids and amendments can be ineffective as they may only reach the mobile porosity in practical timeframes, while the immobile porosity continues to store and slowly release contaminant mass by diffusion across concentration gradients between the immobile and mobile porosity. Geophysical methods offer unique opportunities to investigate the storage of contamination in the rock mass between fractures because they are sensitive to both the mobile and immobile porosity (e.g., Singha et al., 2007; Briggs et al., 2013, 2014).

Geophysical objectives at fractured rock sites fall into two primary categories: (1) characterization of the hydrogeologic framework controlling groundwater flow and contaminant transport and (2) monitoring of contaminant transport and the effectiveness of contaminant remediation strategies. Specific characterization objectives may include determining the location and continuity of major fractures, fracture zones and/or bedding plane features, as well as determining zones of enhanced microscale fracturing. Some borehole geophysical logging technologies have the potential to characterize small, individual fractures intersecting the wall of the borehole, but larger scale geophysical surveys may not have the resolution to see individual fractures. A more ambitious objective of geophysical characterization surveys is the estimation of fundamental rock properties controlling fluid flow, such as permeability. This objective must be viewed with caution as the linkage between geophysical and hydrogeological properties requires support to anchor interpretations. Specific monitoring objectives may include estimating changes in concentrations of the primary contaminants in groundwater, whereas geophysical methods are incapable of seeing individual contaminants (e.g., VOCs at parts-per-million- or parts-per-billion-levels of aqueous concentration) directly. Instead the methods indirectly measure groundwater quality properties such as specific conductance that may be related to contamination levels.

Tracking the spatial extent and distribution of amendments injected into the subsurface is an emerging, valuable application of geophysical monitoring at fractured rock sites. Verification of amendment effectiveness is a challenging problem in site-remediation efforts and the volume of subsurface impacted by the amendment is typically poorly defined from *in-situ* sampling alone. This problem is again accentuated in fracture-rock systems where highly preferential flow occurs through discrete fractures and/or fracture zones.

3. Methods

The geophysical properties of fractured rock are determined by the intrinsic properties of the solid, as well as the liquid and gaseous phases filling fractures. The geometric arrangement and connectivity of fractures also strongly influence certain geophysical properties such as electrical conductivity, to which electrical, electromagnetic, and radar methods are sensitive. The geophysical properties of the fractures themselves are strongly controlled by the fluids filling them. Contaminant transport, delivery and breakdown of amendments for biostimulation, and microbial growth can alter the chemical composition of the fracture-filling fluids, making these processes potentially detectable with geophysical measurements. Reactive transport and remediation treatments may alter the geometry and connectivity of fractures, e.g., through rock dissolution or precipitation of mineral phases such changes are also potentially detectable with geophysical measurements. The electrical properties of fractured rocks are primarily determined by electrolytic conduction occurring through fluid-filled fractures as well as ionic conduction in the electrical double-layer (EDL) forming at fracture-fluid interfaces (*Glover, 2015*). The rock matrix itself (excluding metallic minerals) is a poor conductor and therefore assumed to be an insulator. The dielectric properties controlling ground penetrating radar (GPR) measurements are also strongly controlled by the presence of water and the geometric arrangement of fractures (*Glover, 2015*). Seismic properties of fractured rocks are also fundamentally controlled by the fluids in fractures as a result of the strong difference in seismic velocities and densities between the pore-filling fluids and the mineral matrix (*Schmitt, 2015*). Magnetic properties may be influenced by biogeochemical processes, e.g. those associated with iron cycling (*Moskowitz, 2015*). Contaminant transformations associated with active or natural attenuation can modify magnetic properties through the formation or dissolution of iron minerals (e.g., *Porsch et al., 2010; Rijal et al., 2012*). Consequently, geophysical properties can be related to fracture porosity, fracture connectivity, permeability, water content and the chemical properties of the fracture filling fluids. Therefore, the measurement of variations in these geophysical properties can provide valuable information required to understand the fate of contaminants in the subsurface.

In this section, we provide a brief overview of characterization and monitoring methods appropriate for fractured rock, divided between surface-based methods (Section 3.1), borehole logging methods (Section 3.2), and crosshole methods (Section 3.3). The three classes of methods offer different scales of investigation and resolution, as shown in Figure 3. Surface methods sample the largest volume of aquifer but provide the lowest resolution information, whereas borehole methods provide the best resolution but sample the smallest volume of aquifer; and crosshole methods are intermediate between surface and borehole in terms of resolution and sampled volume. For additional information on the various methods, the reader is referred to Rubin and Hubbard (2005) and Vereecken et al. (2006).

3.1 Surface-Based Methods

Surface-based methods have potential applications for mapping depth to bedrock, thickness of weathered zones, depth to water table, lithology, major faults, and fracture zones. Surface-based methods are commonly incapable of detecting individual fractures at depth, although

detection of shallow fractures may be possible, particularly if fractures are illuminated by tracers with geophysical signatures (e.g., *Talley et al.*, 2005). Although surface-based methods do not offer the resolution possible with borehole or crosshole methods, they are (1) less invasive, requiring no boreholes, and (2) capable of covering much larger areas at lower cost; however, the application of surface methods is limited in areas of substantial infrastructure, such as underground utilities and pipes. Table 1 provides an overview of the information provided by individual methods, but we stress the importance of using a combination of methods, i.e., a “geophysical toolbox” to characterize a contaminated fractured-rock site. An application of surface-based methods to fractured rock is presented subsequently in Section 5.

3.2. Borehole logging methods

Borehole logging geophysical methods (e.g., *Keys*, 1990) are routinely used in site investigations and provide high-resolution information about discrete fracture locations, lithology, fluid properties, and borehole conditions. Commonly, a suite of logs will be collected, because it is cost-effective. The software for data processing and visualization is mature, and comparison of multiple logs collected as a suite can provide valuable insight into geologic structure and fracture orientation statistics. Acoustic and optical televiewer methods provide information about depth and orientation of discrete fractures intersecting boreholes (*Williams and Johnson*, 2004). Borehole logging is also commonly used to guide placement of inflatable packers for hydraulic testing or for design of packer systems for long-term discrete-zone monitoring of water quality and/or hydraulic heads. Caliper, acoustic televiewer, and/or optical televiewer methods are invaluable for identifying potentially viable locations where effective packer/borehole seals are possible. Borehole flowmeter can be used to infer the transmissivity and far-field heads associated with individual fractures (*Day-Lewis et al.*, 2011) in addition to cross-connections between fractures when tests are run between wells (*Roubinet et al.*, 2015). Table 2 provides an overview of the information provided by individual borehole methods, and examples of borehole logs are presented subsequently in Section 5. As for surface-based methods, we stress the importance of using a combination of methods to help constrain interpretation.

3.3. Single-hole and crosshole imaging methods

Single-hole and crosshole imaging methods applied in fractured rock include ground penetrating radar (*Day-Lewis et al.*, 2003; 2006), electrical resistivity (*Slater et al.*, 1997; *Robinson et al.*, 2015), and seismic methods (*Ellefsen et al.*, 2000). Compared to surface-based and borehole methods, crosshole imaging methods are applied rarely, although crosshole electrical resistivity applications have advanced rapidly over the last decade. The resolution of single-hole and crosshole methods is commonly intermediate between those of surface-based and borehole methods. Data from crosshole methods are commonly inverted to produce 2D or 3D images of geophysical properties between wells; however, software for crosshole data analysis is not widely accessible to remediation professionals. The effectiveness of crosshole methods is governed by the offset between wells and the ratio of the vertical-to-horizontal dimensions of the interwell region. Commonly, crosshole radar is limited to well offsets on the order of meters to tens of meters, beyond which the radar signal is too attenuated to be used; crosshole electrical resistivity and induced polarization

are also commonly limited to offsets of tens of meters. Seismic methods are rarely used for environmental applications, as the technology development has focused largely on petroleum and mining applications, and few remediation professionals have access to the necessary equipment. For all crosshole techniques, it is desirable for the imaged region to have an aspect ratio of vertical:horizontal greater than 1, and preferably greater than 1.5. Otherwise, the horizontal resolution is highly compromised and excessive spatial smearing of the targets in the image may result (see Section 4). For all forms of imaging, it is important to note that the images produced represent blurry, blunted versions of physical properties (e.g., *Day-Lewis et al.*, 2005).

Ground penetrating radar can be applied in both (1) transmission mode, which focuses on analysis of electromagnetic energy transmitted through the rock medium between sources and receivers, and (2) reflection mode, which focuses on analysis of electromagnetic energy reflected off of features (e.g., fractures) in the vicinity of boreholes. Reflection data collected from a single borehole can provide information about fracture location and orientation, including fractures that do not intersect boreholes (e.g., *Olsson et al.*, 1992). Indeed, radar-reflection logs have been used to infer statistics on fracture populations for stochastic modeling of discrete fracture networks (*Dorn et al.*, 2013). Table 3 provides an overview of the information provided by imaging methods. Examples of imaging methods are presented subsequently in Section 5.

4. Method selection

Appropriate method selection is paramount for successful characterization or monitoring campaigns. Following best practices, method selection is guided by “pre-modeling” or “synthetic modeling” to predict how a given geophysical method would “see” a hypothetical target. Synthetic numerical modeling of geophysical datasets can be used to evaluate whether specific geophysical measurements at fractured-rock sites are likely to be worthwhile, providing an objective basis for go/no-go decisions. Figure 4 shows schematically the synthetic modeling workflow a sequence of steps to determine whether a specific target of interest is likely to be resolvable. The approach requires defining the geophysical properties and dimensions of the target and the geophysical properties of the background medium, which could be heterogeneous. Given these considerations, tools exist to generate synthetic datasets that represent the data that would be acquired in the field. Hydrogeological and geochemical data available from the site should be used in this procedure. These synthetic datasets can then be corrupted with random noise to better represent true field data. The noisy datasets are inverted to examine whether the target is likely to be detectable with the selected geophysical methods. This usually represents a test under idealized conditions as the true subsurface heterogeneity is likely to be much more complex than the synthetic model, and real errors may not follow assumed probability distributions; however, even if for idealized conditions, synthetic modeling provides valuable insight into the strengths and limitations of methods with respect to the study objectives. In addition to providing a basis for a decision to use a particular geophysical method, synthetic modeling also provides valuable insight for interpretations of geophysical results and differentiation of numerical artifacts from geophysical targets.

Commercial and open-source software is available to perform such pre-modeling exercises for most established geophysical methods (e.g. resistivity, seismic, ground penetrating radar). Such software allows the user to enter a hypothetical geophysical property structure and the layout of the sensors used in the geophysical survey. The software then calculates the theoretical measured geophysical data that would result from a survey. The user may corrupt the data with random errors, analyze the data as they would real field data, and assess the resulting geophysical image.

An example for a hypothetical light non-aqueous phase (LNAPL) target is provided for a surface-based resistivity survey in Figure 5. A hypothetical LNAPL spill is considered (Figure 5a), with some residual LNAPL in the unsaturated zone and LNAPL pooling on the water table. Although the survey detects the presence of the LNAPL, which manifests as a low-resistivity anomaly (Figure 5b), the lateral extent and vertical extent of the plume are poorly resolved. Based on this result, use of a surface-based electrical resistivity would not be recommended if study goals focused on (1) identification of plume extent, or (2) inference of plume thickness to ± 1 m. On the other hand, if study goals were to identify a depth to LNAPL within ± 2 m, the survey might be warranted. It should be noted that this example neglects geologic heterogeneity, which would serve to further mask the target. In addition to providing a basis for a go/no-go decision on the use of geophysical methods, synthetic modeling also provides valuable insight for interpretation of geophysical results and evaluation of resolution.

The example presented in Figure 5 was developed using new, draft software that streamlines synthetic modeling of electrical resistivity surveys for a suite of common environmental targets, e.g., LNAPL and dense non-aqueous phase liquid (DNAPL) pools and discrete fractures.

Although pre-modeling represents best practice, application of the approach is not yet widespread outside of the research community because of the specialized nature of the necessary software. Simpler tools may, therefore, help for remediation professionals in their consideration of the use of geophysical methods. Technology-transfer tools have been developed to help the site investigation professional make more informed decisions about the potential application of geophysical technologies to fractured-rock sites. A Fractured Rock Geophysical Toolbox-Methods Selection Tool (FRGT-MST) was developed under Department of Defense funding (ESTCP ER-201118) and with funding from the U.S. Environmental Protection Agency (EPA) (Day Lewis et al., 2016). The FRGT-MST is a user-friendly Excel-based software for identification of geophysical methods likely to be appropriate and effective for a given set of project goals based on site conditions. This 'toolbox' comprises 30 different geophysical methods divided into 4 categories: surface, crosshole, borehole, and hydrogeologic. The user enters information into two tables: (1) project and site parameters, including site geology, well constructions, and survey budget level; and (2) project goals, such as characterization of major fracture zones, characterization of discrete fractures, and monitoring remedial activities. A third table is populated with indicators for whether each method could potentially support any of the specified goals, and whether each method is likely to work at the site described. Methods that are both appropriate and feasible represent the suite of potentially suitable methods for the project.

Figure 6 provides an example application of the FGRT-MST to the Naval Air Warfare Center, a fractured-rock site in West Trenton, NJ, which is contaminated with chlorinated solvents. Based on the site geology, the FGRT-MST rules out application of radar methods, which would likely perform poorly in the region's electrically conductive mudstone bedrock, which tends to attenuate radar signals.

5. Examples

In this section, we present three case studies to illustrate the potential of surface-based, borehole logging, and crosshole imaging geophysical methods for fractured-rock investigations. Despite the presentation of each case study as focused on a different class of methods, we emphasize the importance of using methods in combination. Indeed, each of the three case studies involved the use of multiple methods and in some cases surface-based, borehole logging, and imaging. Method selection was guided by the principles discussed previously, in Section 4, and knowledge of the sensitivity of methods to hydrologic properties and targets, as summarized in Tables 1–2. We showcase only a small subset of data from each site in the brief summaries below.

5.1. Example 1. The UConn Landfill, Storrs, CT, USA

One of the foremost challenges in studies of fractured rock is the development of a 'conceptual site model' (CSM) describing flow patterns, contaminant distribution, and contaminant migration pathways. CSM development is commonly iterative and involves integration of information as it becomes available from drillers' logs, hydraulic testing (e.g., slug tests, packer tests), observations of hydraulic head, chemical sampling, structural geology and geologic mapping, and geophysics. We present a study from a former University of Connecticut (UConn) landfill, located in Storrs, CT, where the U.S. Geological Survey (USGS) has conducted multi-method geophysical and hydrogeological characterizations to support design of the site remedy (*Johnson et al.*, 2005). One of the important lessons learned from the geophysical work at the landfill was how open boreholes can connect fractures or fracture zones with different hydraulic head and, thus, provide vertical conduits for flow and contamination. A second lesson learned was the value in interpreting water chemistry samples in the context of vertical flow in wells. Contaminant concentration can vary dramatically above and below a fracture, depending on the direction of flow in the borehole. A series of reports on this project form the basis for training material used by the USGS in training and technology transfer to the EPA and industry. For additional details about these studies, the reader is referred to *Johnson et al.* (2005, 2002a, 2002b).

The UConn landfill site is in an upland region of the Willimantic River Basin in Connecticut, where domestic water supply relies heavily on bedrock wells. Contamination from the landfill and former chemical-waste disposal pits migrated into crystalline bedrock underlying the site, and VOCs were found in domestic bedrock wells in the area during the mid-1980s. The USGS initiated work in 1999 in collaboration with the university and site remediation professionals. The USGS work focused on (1) surface geophysics, including electrical, electromagnetic induction, and seismic refraction surveys, (2) borehole

geophysical logging, including an extensive suite of logs (discussed below), and (3) discrete-zone monitoring, in which fractures were isolated for measurements of hydraulic head and for chemical sampling.

Surface electrical and electromagnetic induction surveys (Figure S1 in the Supplemental Material) were used to target potential discharge of contaminants, manifesting as elevated total dissolved solids (TDS) and, thus, electrical conductivity. Although VOCs at ppb or ppm levels would not strongly affect fluid electrical conductivity, landfill leachate is commonly high in TDS. Borehole geophysical methods were used to investigate the anomalies identified by surface geophysical methods. Televiewer (acoustic and optical) (Figure S2) and reflection-mode radar data were used to study individual fractures that intersect and surround each well, and to determine fracture depths and orientations. Using a borehole flowmeter under ambient and stress conditions, transmissive fractures were identified and the direction and magnitude of ambient borehole flow were measured. Borehole geophysical and hydraulic data were used to design discrete-zone monitoring systems for the collection of hydraulic head and chemical data and to prevent cross contamination through the boreholes. The combination of surface geophysics and borehole geophysics provided for a multi-scale characterization, and the use of direct hydrologic testing and sampling provided a basis for interpretation of the indirect geophysical information.

The CSM of groundwater flow and contaminant distribution (Figures S3, S4, respectively) was developed iteratively and refined as the results of the geophysical, hydraulic, and chemical data became available. The CSM was used to assess contaminant migration from the landfill and chemical-waste disposal pits and to evaluate remedial alternatives. The CSM includes two contaminant migration pathways—one pathway discharges into a wetland and ultimately dissipates to background levels; and the other seeps into bedrock, where it can be traced based on water chemistry. The migration pathways are oriented north-south, which coincides with a dominant fracture set identified by the geophysical surveys.

5.2. Example 2. Machiasport, ME, USA

The single-hole radar reflection method (*Olsson et al.*, 1992) is a powerful approach for identifying the location, orientation and extent of discrete fractures. In contrast to televiewer methods, which can identify the orientations of fracture intersecting borehole walls, the single-hole radar reflection method can image fractures located meters to tens of meters from the borehole. The method can be combined with ionic (e.g., sodium chloride) tracer tests to image tracer transport in discrete fractures, providing valuable insight into fracture connectivity and permeability. Although this technique was developed more than 20 years ago and has been applied successfully at major fractured-rock research sites (e.g., the Stripa Mine in Sweden and the USGS Mirror Lake site in NH), it is rarely used outside of academia and the research community. We present a case study from Machiasport, ME, to highlight the potential of this approach for understanding fracture architecture. Interest in the single-hole radar reflection method is increasing with recent interest in the discrete-fracture network (DFN) approach to site characterization and modeling (*Parker et al.*, 2012). For additional details of the methods and results of this case study, the reader is referred to *Johnson and Joesten* (2005).

The USGS, in cooperation with the U.S. Army Corps of Engineers, collected borehole-radar reflection logs in Machiasport, ME, to identify the depth, orientation, and spatial continuity of fractures that intersect and surround two boreholes (*Johnson and Joesten, 2005*). In addition, the results were used to (1) identify the radial depth of penetration of the radar waves in the electrically resistive volcanic formation at the site, (2) provide information for locating additional boreholes at the site, and (3) test the potential applications of borehole-radar methods for further aquifer characterization and/or evaluation of source-area remediation efforts.

The two bedrock boreholes were drilled as part of an investigation of the area surrounding the former Air Force Radar Tracking Station site on Howard Mountain near Bucks Harbor. The boreholes, MW09 and MW10, were located approximately 50 m from, and at the site of, respectively, the locations of former buildings where trichloroethylene was used as part of defense-site operations. These areas were thought to be potential source areas for contamination that was detected in downgradient bedrock wells.

Borehole-radar reflection logging uses a pair of downhole transmitting and receiving antennas to record the reflected wave amplitude and transit time of high-frequency electromagnetic waves. For this investigation, 60- and 100-megahertz antennas were used. The electromagnetic waves emitted by the transmitter penetrate into the formation surrounding the borehole and are reflected off of a material with different electromagnetic properties, such as a fracture or change in rock type. Single-hole directional radar surveys indicate the bedrock surrounding these boreholes is highly fractured, because several reflectors were identified in the radar-reflection data. There are several steeply dipping reflectors with orientations similar to the fracture patterns observed with borehole imaging techniques and in outcrops. For the radar surveys collected at this site, radar reflections were detected up to 40 m into the rock from the borehole. These results indicate that boreholes could conservatively be spaced about 15–20 m apart for hole-to-hole radar methods to be effective for imaging between the boreholes and monitoring remediation.

The depths and orientations of reflectors identified from borehole MW10 are shown in Figure S5 and Figure S6. In Figure S5, results are presented in the form of fracture projections, tadpole plots, and stereoplots tools commonly used by structural geologists. In Figure S6, interpreted fractures are visualized as planar disks in three dimensions. Maps of the intersections of fractures with ground surface (Figure S7) provide valuable information for siting wells to achieve (or avoid) hydraulic connections with existing wells or to understand possible contaminant or amendment migration pathways. To support the design of radar data collection and interpretation of results, a suite of borehole geophysical logs were collected, including natural gamma, electromagnetic (EM) induction, normal resistivity, spontaneous potential, and single-point resistance logs. Mechanical caliper, acoustic televiewer (ATV), and optical televiewer (OTV) logs were used to identify the location and orientation of fractures that intersect the borehole.

5.3. Example 3. Cross-borehole electrical monitoring of amendment injection into fractured rock

Cross-borehole electrical imaging of amendment injections into fractured rock was demonstrated at the former Naval Air Warfare Center (NAWC), located in West Trenton, NJ (USA) (Slater *et al.*, 2015). The fractured bedrock aquifer at this site is extensively contaminated with the chlorinated solvent trichloroethylene (TCE) and fractures and the rock matrix are contaminated with TCE and its biotic degradation products cis-dichloroethylene (cDCE) and vinyl chloride (VC). The site consists of fractured sedimentary rocks of the Newark Basin. Dominant contaminant transport pathways are through (1) a series of cross-cutting faults and (2) discrete fracture zones associated with carbon-rich intervals (Lacombe and Burton, 2010). Seven, 3.8-inch-diameter boreholes (denoted 83-89BR, Figure S8) were drilled and left uncased through the unweathered mudstone units. In this unique demonstration experiment, the borehole array was specifically designed to favor cross-borehole electrical imaging of amendment transport following injection into a packed off interval straddling a permeable fracture zone characterized by high contaminant concentrations.

Several tracer tests were conducted prior to the final amendment injection (Robinson *et al.*, 2015), resulting in a final design based on pulse-injection of amendment into an outer borehole performed in July 2014. A molasses amendment was spiked with sodium bromide to increase the electrical conductivity contrast due to amendment injection and transport. Sixty (60) L of the spiked amendment were injected into borehole 87BR (Figure S8) over 17 time intervals. Electrical imaging measurements were collected after each injection interval, following the injection and continuing for up to 64 days beyond the last injection. Inverted images of changes in electrical conductivity since the start of the amendment injection (Figure S8a) capture the evolution of a conductive plume beginning at the injection borehole (87BR), migrating towards 83BR and then evolving to move towards 85BR (Figures S8 b–d). Fourteen days following the amendment injection (Figure S8e), the highest conductivity changes are at about 29-m depth in 87BR and between boreholes 83BR and 85BR. The electrical signature of the amendment is clearly diminished at 64 days (Figure S8f) following the injection. Direct measurements of specific conductance and major ion chemistry from isolated intervals in boreholes that intercepted the amendment transport provided supporting ground-truth data to validate the electrical images (see Slater *et al.*, 2015 for details). Geologic data and hydraulic connections inferred from cross-borehole testing (see Robinson *et al.*, 2015 for details) are also consistent with the transport pathways imaged.

Such time-lapse electrical geophysical measurements provide invaluable plot-scale information capturing preferential migration pathways during amendment injection. The 3D images of the amendment injection highlight transport dynamics within this heterogeneous fractured-rock system that could not have been resolved using standard borehole geophysical logging methods or hydraulic testing alone. For example, while the geophysical images generally show amendment transport down-dip in the direction of strike, a complex, channelized flow behavior is revealed, particularly in the transport of the amendment around

86BR. These images show strong evidence for channelized flow within a fracture zone and provide unique temporal information on the evolution of the amendment into this zone.

6. Discussion and conclusions

The characterization, monitoring and remediation of fractured-rock aquifers remain major challenges facing remediation professionals. Conventional site investigations based on direct borehole observations, hydrogeologic tests (e.g., slug tests), and sampling cannot capture the hydrogeological complexity controlling flow and transport in fractured rock. Geophysical methods provide the means to see beyond and between boreholes, and some methods can identify the locations and orientations of discrete fractures. Geophysical methods are used increasingly at fractured-rock sites. Some geophysical methods (e.g., logging) are well established as state-of-the-practice and widely used and accepted, while other approaches (e.g., imaging methods) are currently transitioning from research to practice with the support of demonstration projects and technology-transfer efforts. Surface-based, borehole logging and imaging methods offer different ranges of scales, diversity of measurements, and information content. Understanding how to select and combine methods is of paramount importance to enable more widespread application of geophysics.

A major impediment to the adoption of geophysical methods by remediation professionals is lack of access to tools to assess the range of geophysical methods likely to be applicable for a given site and specific objectives. Synthetic modeling represents a powerful approach to understanding the capabilities and limitations of geophysical methods to achieve different objectives. Although synthetic modeling tools are available and widely used in research, applications in the environmental industry are uncommon. Simple tools for method selection and rejection are needed. Toward this end, the FRGT-MST provides decision support for method selection based on simple user inputs about site conditions, budget level, and project goals, thereby empowering site remediation professionals to make informed decisions about the expected usefulness of specific geophysical methods. Ideally, the FRGT-MST (or similar tools) would guide initial study design, and synthetic modeling would then be performed prior to expending the time and expense of a field survey. Synthetic modeling will never guarantee that a geophysical method is going to work at a specific fractured-rock site, but it will show when application of a method for a specific situation is likely to be futile. Streamlined synthetic modeling tools could help to advance the use of synthetic modeling in practice.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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imply endorsement by the U.S. Government. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. EPA. The FRGT-MST tool can be downloaded from <https://water.usgs.gov/ogw/bgas/frgt/>.

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Figure 1.

Schematic showing concept of mobile and immobile porosity in fractured rock. (a) Upon release of a contaminant at a fractured-rock site, contamination migrates through the overburden into permeable, connected fractures. (b) Over time, contamination spreads throughout the network of permeable, connected fractures and diffuses into the rock matrix and less connected, less permeable, or dead-end fractures. (c) After source removal and onset of the aquifer remedy, the network of permeable, connected fractures is remediated but contamination persists in the rock matrix in primary porosity and less connected, less permeable, or dead-end fractures. (after Parker et al., 2012).

Figure 2.

In many fractured-rock systems it is useful to conceptualize the rock as comprising two domains: (1) the mobile porosity (blue) consisting of connected permeable fractures, and (2) the immobile porosity (red) consisting of dead-end, disconnected or impermeable fractures and the rock matrix. Advection of solutes occurs only in the mobile porosity, and exchange occurs locally between the two domains according to various forms of diffusive rate-limited mass transfer (*Carrera et al., 1998*).

Figure 3. Schematic diagram showing the tradeoff between scale of investigation and resolution for borehole, crosshole, and surface geophysical methods (after *Rubin and Hubbard, 2005*).

Figure 4.

Synthetic modeling workflow for various geophysical methods constituting four steps: (1) Assign best-guess physical properties for the hypothetical subsurface model; (2) forward model, i.e., calculate the data that would result from the assumed 'true' model entered by the user in the first step and corrupt the data with random errors for realism, generating 'synthetic data'; (3) analyze the synthetic data by inverse modeling to produce an image, or tomogram; and (4) compare the inverted synthetic image with the assumed true model. If the synthetic image does not sufficiently resolve the target sought, i.e., a light non-aqueous phase liquid plume in this schematic, the method will likely fail and should be rejected.

Figure 5. Pre-modeling example with (a) a hypothetical target consisting of a light non-aqueous phase (LNAPL) plume on the water table, and electrodes with 1-m spacing at land surface; and (b) the electrical resistivity tomogram that would result, assuming normally distributed random standard errors of 3%.

(a) Application of the FRGT-MST to data and specifications of the Naval Air Warfare Center contaminated fractured-rock site in West Trenton, NJ, USA (from *Day-Lewis et al.*, 2016); (b) Enlarged view of the ‘Project and site parameters’ table from (a); (c) Zoomed in ‘Goals’ table from (a); and (d) the resulting Go/No-Go recommendation and results for use of borehole radar at the site. Use of radar at the site is contraindicated based on the Site Parameter 2 (electrical resistivity), despite indications that the method would contribute to study Goals A and B (identification of discrete fracture network characteristics and lithologic contacts).

Table 1

List of surface-based geophysical methods commonly used in fractured rock. The extent and depth of the survey region and the resolution are all approximate ranges. The measured parameters can be derived directly from the acquired data. The recovered properties are obtained through processing and/or inversion of the acquired data.

Method	Lateral Extent of Survey Region (meters)	Depth of Survey Region (meters)	Resolution (meters)	Measured Parameters	Recovered Properties of Interest	Potential Fractured Rock Targets
Electrical Resistivity	1 to 100	1 to 100	0.5 to 10	Electrical potential from applied current	DC electrical conductivity	Fracture zones, Amendment monitoring
Ground Penetrating Radar	1 to 1000	1 to 50	0.1 to 10	Amplitude and arrival time of reflected EM energy	Dielectric constant at frequencies of 1MHz to 1GHz	Major fractures, fracture zones, transport in fractures
Electro-magnetic induction	1 to 10000	1 to 100	0.5 to 10	Induced magnetic fields due to sub-surface conductors	Electrical conductivity	Contaminant plume delineation
Very low frequency EM	1 to 10000	5 to 75	1 to 10	Secondary fields from navigational signals	Electrical conductivity	Faults, fracture zones
Magnetometry	1 to 10000	1 to 100	0.5 to 10	Magnitude and/or gradient of Earth's magnetic field	Magnetization, magnetic susceptibility	Treatment monitoring (metals)
Seismic Reflection/Refraction	1 to 1000	1 to 500	1 to 10	Amplitude and arrival time of reflected elastic energy	Elastic wave velocities, attenuation	Depth of weathered zone, major fractures
Induced Polarization	1 to 1000	1 to 100	0.5 to 10	Decay in electrical potential following current pulse; frequency dependence of complex impedance	Imaginary part of the complex electrical conductivity at frequencies from mHz to kHz	Permeability estimation, amendment monitoring
Surface Nuclear Magnetic Resonance	10 to 100	1 to 100	1 to 10	Decay in nuclear magnetization following radiofrequency pulse	Relaxation time constant	Depth to groundwater, permeability, water content
Self Potential	1 to 1000	1 to 100	0.5 to 10	Electrical potentials arising from current sources in the earth	Electrodiffusion potential, redox potential, streaming potential	Groundwater flow directions

Table 2

Details of borehole geophysical logging methods commonly applied to fractured rock. The lateral radius of penetration into the formation and resolution of the measurement, are approximate ranges for site investigation. The measured parameters can be derived directly from the acquired data. The recovered properties are obtained through processing and/or inversion of the acquired data.

Method	Radius of Penetration (meters)	Resolution (vertical) (meters)	Measured Parameters	Recovered Properties of Interest	Potential Fractured Rock Targets
Caliper	N/A	0.05	Diameter of borehole	Diameter of borehole	Fracture locations, guidance for packer placement
Electro-magnetic induction	0.5	0.5	induced magnetic fields due to subsurface conductors	Electrical conductivity	Contaminant plume delineation
Magnetic Susceptibility	0.5	0.5	Magnetic susceptibility	Magnetic susceptibility	Iron minerals (magnetite). Treatment monitoring involving metals
Sonic logging	0.2 to 1	0.1	Arrival time of compression, shear, and Stoneley waves	Compressional wave velocity shear wave velocity tube wave velocity	Porosity, lithology, cement bond evaluation; fracture evaluation, lithology, mechanical properties fracture permeability
Single Point Resistance	N/A	0.05	Resistance	Resistance	Characterization of lithology
Normal Resistivity	0.2 to 1.6	0.05 to 1.6	Electrical potential in response to injected current	Electrical resistivity	Major fracture detection, lithology, solute or amendment monitoring
Nuclear Magnetic Resonance	0.3	0.25 to 1	Decay in nuclear magnetization following radio-frequency pulse	Relaxation time constant	Porosity, permeability
Self Potential	N/A	0.5	Electrical potentials arising from current sources in the earth	Electro-diffusion potential, redox potential, streaming potential Thermoelectric potential	Groundwater flow directions
Fluid conductivity/temperature	None	0.05	Fluid electrical conductivity, temperature	Fluid electrical conductivity, temperature	Total dissolve solids, fracture locations, solute or amendment monitoring
Television	None	0.05	Visual inspection	Video or digital image	Fracture locations, lithology, formation of precipitates, turbidity, flocculation due to amendments
Acoustic Televiwer	None	0.0005	Ultrasonic reflection, amplitude and traveltime	Acoustic reflectivity and borehole diameter	Fracture locations and orientations, lithology, borehole diameter
Optical Televiwer	None	0.0005	Visual	Red, green, blue color and light intensity	Fracture locations and orientations, lithology
Flowmeter	1 to 100	N/A	Heat-pulse travel time or impeller speed	Vertical flow	Transmissivity and far-field head of fractures or layers

Table 3

Details of four single-hole and crosshole geophysical imaging methods with potential application to fractured rock. The lateral extent and depth of the surveyed region, and resolution of the measurement, are all typical values for environmental site investigation. The measured parameters can be derived directly from the acquired data. The recovered properties are obtained through processing and/or inversion of the acquired data.

Single-hole and Crosshole Geophysical Imaging Methods	Resolution of Measurement (meters)	Measured Properties	Recovered Parameters of Interest	Potential Fractured-rock Targets
Electrical Resistivity tomography	0.1 to 10	Electrical potential generated by transmission of current	DC electrical conductivity	Fracture zones, Amendment monitoring
Ground Penetrating Radar (transmission tomography)	0.1 to 5	Arrival time and amplitude of transmitted electromagnetic energy	Electromagnetic velocity at antenna frequency (between 60MHz and 250MHz) and attenuation	Major discrete fractures, fracture zones, transport in fractures
Ground Penetrating Radar (reflection)	0.1 to 1	Arrival time and amplitude of reflected electromagnetic energy	Locations and orientations of reflectors	Locations and orientations of discrete fractures
Seismic transmission tomography	1 to 5	Amplitude and arrival time of transmitted elastic energy	Elastic wave velocities, attenuation	Fracture zones, lithology