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Research article

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

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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.

## 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

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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; 2015; 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

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