USE OF A GEOPHYSICAL TOOLBOX TO CHARACTERIZE GROUND-WATER FLOW IN FRACTURED ROCK

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INTRODUCTION

The characterization of ground-water flow in fractured-rock is a challenging problem. In 1989, the U.S. Geological Survey (USGS), under the Toxic Substance Hydrology Program, established a fractured-rock research site in the Mirror Lake watershed at the Hubbard Brook Experimental Forest, Grafton County, New Hampshire. The goals of this project were to study the processes that control the fate and transport of chemicals in fractured rock over scales from tens of meters to kilometers, apply a multidisciplinary approach to the problem, and develop field methods that could be transferred to other fractured-rock sites. As part of this work, several geophysical methods were developed or tested and an approach evolved for the integrated use of these methods. The overall multidisciplinary approach to characterizing fractured rock is described in Shapiro et al. (1999) and a general outline of this process is shown in Figure 1. This abstract discusses the application of surface- and borehole-geophysical methods in the characterization of ground-water flow in fractured rock. Surface geophysical methods provide site reconnaissance suitable for the development of initial conceptual models of ground-water flow in the formation and the siting of test drilling. Conventional borehole-geophysical logs, borehole imaging, and advanced single- and cross-hole geophysical methods can be interpreted to identify the location and physical characteristics of fractures, and, potentially, their hydraulic properties. Integration of surface- and borehole-geophysical data with geologic, hydrologic, and geochemical data provides a means for development of a comprehensive interpretation of the hydrogeologic conditions at a site and a conceptual understanding of ground-water flow.

The Total Toolbox

- **Historical review of site**
- **Geology**
- **Surface geophysics**
- **Drilling**
- **Prevention of cross contamination**
- **Borehole geophysics**
- **Hydrologic testing and tracer tests**
- **Discrete interval completion**
- **Chemical sampling**
- **Modeling**
- **Integrated interpretation**

FIGURE 1. Outline of the toolbox method for characterization of ground-water flow in fractured rock.

SURFACE-GEOPHYSICAL METHODS

A wide variety of surface-geophysical methods have been used in fractured-rock investigations (Lewis and Haeni, 1987). As a result of the USGS research at Mirror Lake and other sites, several surface-geophysical methods have been shown to characterize the bulk anisotropy of the site or to delineate physical property anomalies in the rock. Azimuthal direct-current (DC) resistivity can detect bulk anisotropy changes with depth (Lane et al., 1995) and in some cases can be related to the dominant fracture direction at the site. Two-dimensional (2D) DC resistivity (Fig. 2) and electromagnetic methods

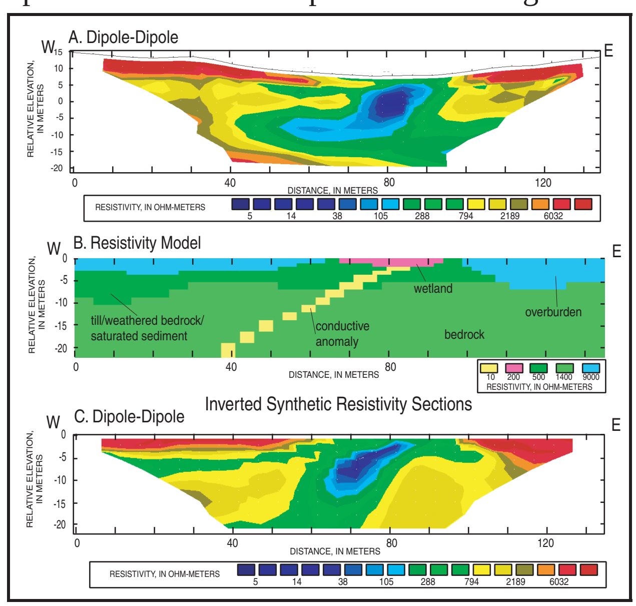

FIGURE 2. Inverted resistivity section of two-dimensional direct-current resistivity data for line 2DL6, University of Connecticut landfill, Storrs, Connecticut (after Powers, Wilson, et al., 1999). A. Inverted resistivity section of dipole-dipole data. B. Resistivity model. C. Inverted synthetic resistivity data. The data were generated using the model in (B).

(Powers, Singha, and Haeni, 1999; Powers, Wilson, et al., 1999) have been shown to detect fracture zones and conductive lithologic features. Other surface-geophysical methods have and can be used depending upon the geology and site conditions. Upon integration of the interpreted surface-geophysical data and other site data, optimum locations and depths of test holes can be determined to investigate individual geophysical anomalies or general ground-water geochemistry and potential contaminant migration (Powers, Wilson, et al., 1999; Johnson et al., 2001).

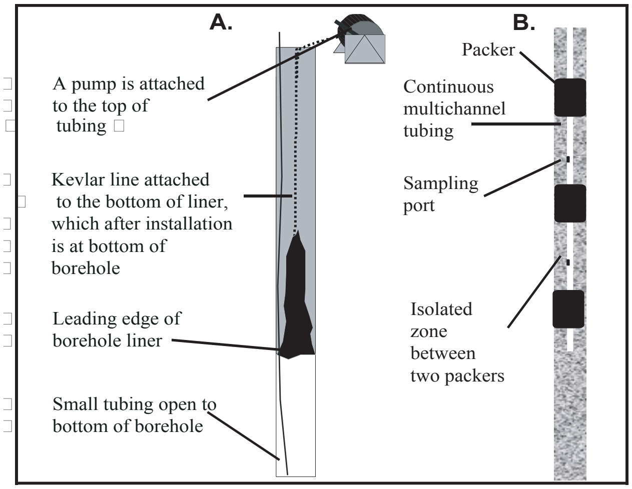

FIGURE 3. A. Schematic diagram of installation of a well liner in a borehole. The sock is inverted and banded to the outside of the casing. The sock is pulled off the reel and pushed into the top of the well, and water is added to invert and drive the sock down the well while water is extracted simultaneously from below the sock by means of a tube that is extended to the bottom of the well. B. Discrete zone monitoring system.

PREVENTION OF CROSS-CONTAMINATION

In the test holes, the borehole-geophysical methods are used to measure fluid properties as well as rock properties. In the open borehole, cross-connection of fracture zones with different hydraulic heads and ground-water chemistry can cause artificial alteration in fluid properties and cross-contamination (Williams and Conger, 1990). Flow between fracture zones and cross-contamination can be prevented by installing well liners or packers to hydraulically isolate fracture zones. A sketch of a liner being installed in a borehole is shown in Figure 3. These liners can be installed immediately after drilling, removed for borehole-geophysical work, and then reinstalled until a final borehole completion system is designed and ready for installation. This approach prevents cross contamination, thereby allowing representative water-quality samples to be collected from hydraulically isolated fracture zones (Fig. 3) (Johnson et al., 2001).

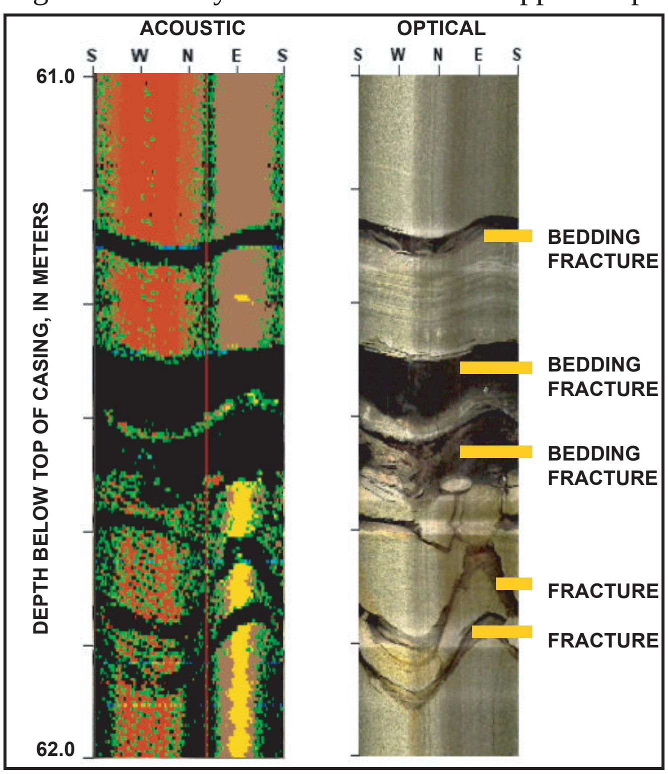

FIGURE 4. Acoustic- and optical-televiewer images of a transmissive zone at 201 feet in borehole RD-35B, Rocketdyne Santa Susana Field Laboratory, Ventura County, California (Williams et al., in press).

BOREHOLE-GEOPHYSICAL METHODS

Upon completion of the test holes, conventional and advanced borehole-geophysical methods and hydraulic testing methods are used to characterize the physical and hydrologic properties to develop a conceptual model of ground-water flow in fractured rock at the site. This is done by identification and analysis of the orientation and depth of lithologic features and hydraulically active fractures or fracture zones in the borehole, the physical condition of the hole, and the fracture zones or geologic discontinuities that are near but do not intersect the borehole. Conventional borehole logs consisting of temperature, caliper, resistivity, gamma, and fluid conductivity logs (Keys, 1990; Hearst et al., 2000) are routinely run and interpreted in conjuction with data from advanced logging methods. The advanced borehole methods consist of acoustic and optical borehole wall imaging (Fig. 4), borehole flow meter logs under ambient and pumped conditions, and borehole radar (Fig. 5) (Williams and Johnson, 2000; Johnson et al., in press; Williams et al., in press). In some cases, seismic, radar, or DC-resistivity tomography is used to image the rock between holes or to image flow paths of tracers. (Ellefsen et al., 1999; Lane et al., 2000).

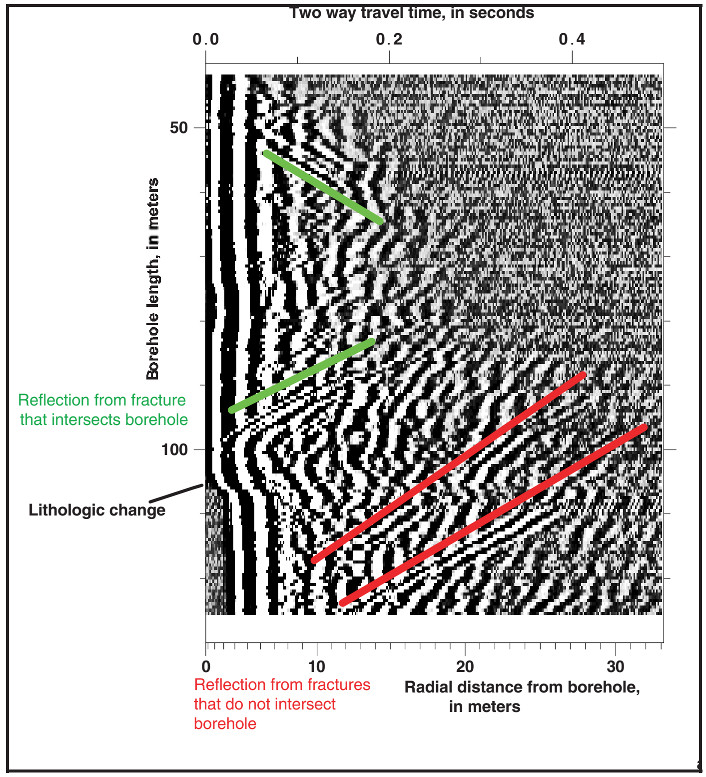

FIGURE 5. Directional borehole radar data, at 60 megahertz, from a borehole in Queens County, New York. The material resistivity increases with depth permitting greater penetration of the radar waves. There is a change in material at a depth of about 105 meters. Examples of reflections from water-filled fractures that intersect and do not intersect the borehole are shown.

INTEGRATED INTERPRETATION

One of the most important steps in characterization of the hydrogeology of fractured rock is the integrated interpretation of the surface- and borehole-geophysical data, and their integration with other hydrologic, geologic, and geochemical data (Lane et al., 1996). An example of the integration of surface- and borehole-geophysical data is shown in Figure 6, where the interpreted bedrock anisotropy from the azimuthal square array is shown. From the borehole data, the strike and dip of hydraulically active fractures are differentiated from both other fractures and the fabric of the rock (Fig. 6B and 6C). The geophysical data, when incorporated with other data, had a major impact on the understanding of fluid flow and contaminant transport at the site (Lane et al., in press).

CONCLUSIONS

A methodical approach to characterizing ground-water flow in fractured rock has been developed. Data from surface- and borehole-geophysical surveys are integrated with geologic, hydrologic, and geochemical data in order to develop a comprehensive conceptual model of ground-water and contaminant flow in fractured rock. This conceptual model, based on the integration of scientific data, can then be used by regulators and site owners to determine appropriate remediation solutions.

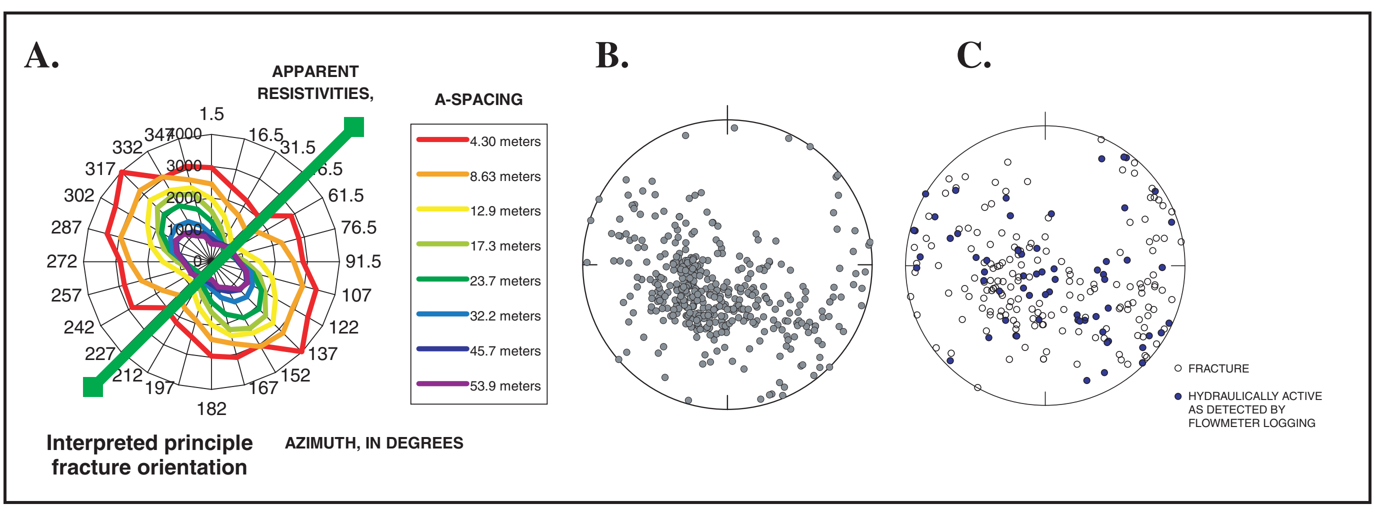

FIGURE 6. A. Results of azimuthal resistivity, Square Array 1, Norwalk, Connecticut. The A-spacing is the length of the side of the square. Equal-area stereonets of (B) foliation and (C) fractures in 11 wells at the study site in Norwalk, Connecticut. From Lane et al. (2001).

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