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Characterizing Ground-Water Chemistry and Hydraulic Properties of Fractured-Rock Aquifers Using the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT³)

Characterizing Fluid Movement and Chemical Transport in Fractured-Rock Aquifers

In many aquifers in the Nation, cracks, joints, and faults (collectively referred to as "fractures") act as the principal conduits of ground-water flow. In these fractured-rock aquifers, water-resources managers and hydrologists responsible for issues ranging from water supply to the restoration of contaminated ground water need to assess the availability of ground water and the potential for contaminant migration.

Water-resources managers and hydrologists drill boreholes in fractured-rock aquifers to collect hydraulic and chemical data needed to characterize fluid movement and chemical transport. Data collected from boreholes in fractured-rock aquifers, however, may yield ambiguous interpretations because a borehole acts as a high permeability pathway that connects fractures, which previously were unconnected. Open boreholes act to integrate hydraulic and chemical data from all fractures intersecting the borehole. Collecting hydraulic and chemical data in open boreholes does not quantify variability in ground-water chemistry or hydraulic properties, which is crucial in conceptualizing fluid movement and chemical transport in fractured-rock aquifers.

Borehole packers reduce or eliminate the effect that open boreholes have on the collection of hydraulic and chemical data. Borehole packers are pneumatic or mechanical devices that isolate sections of a borehole by sealing against the borehole wall. Hydraulic tests or collecting ground-water samples for chemical analyses then can be conducted on the isolated section of the borehole.

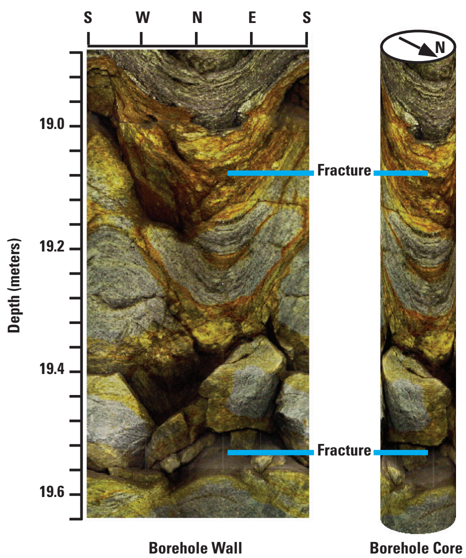

Figure 1. Oriented digital image (S=South, W=West, N=North, E=East) of a borehole wall and core synthesized from a digital borehole camera. Geophysical logging tools, such as the digital borehole camera (see, for example, Williams and Lane, 1998), provide critical information about borehole conditions to design the location of hydraulic tests and the collection of water samples conducted by the Multifunction BAT³.

Figure 2. A borehole packer with inflatable bladder is being prepared for installation in a bedrock borehole. The packer is supported by a pipe and lowered down the borehole using a truck-mounted winch.

Many types of hydraulic tests and chemical sampling configurations can be designed using borehole packers. Thus, equipment used for hydraulic testing and collecting ground-water samples for chemical analyses usually has been constructed for a specific need at a specific site. The physical dimensions of the downhole equipment and the need for various peripheral components at land surface for data collection and data processing have made borehole testing equipment cumbersome and not readily portable from site to site.

The Multifunction BAT³

The U.S. Geological Survey (USGS) has a patent pending on a Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT³). The equipment is designed to perform the following operations by isolating a fluid-filled interval of a borehole using two inflatable packers:

(1) collect water samples for chemical analysis,

(2) identify hydraulic head,

(3) conduct a single-hole hydraulic test by withdrawing water,

(4) conduct a single-hole hydraulic test by injecting water, and

(5) conduct a single-hole tracer test by injecting and later withdrawing a tracer solution.

The equipment also can be configured to conduct these operations with only one of the borehole packers inflated, dividing the borehole into two intervals (above and below the inflated packer).

The Multifunction BAT³ is designed with two inflatable packers and three pressure transducers that monitor fluid pressure in the test interval (between the packers), as well as above and below the test interval; pressure transducers above and below the test interval are used to ensure that the borehole packers seal against the borehole wall during applications. The Multifunction BAT³ is designed with digital data-acquisition capabilities to collect time-varying pumping or fluid-injection rates and fluid-pressure responses. Data acquisition is integrated with a laptop computer to store and display data in real time. Interpretation of fluid-pressure responses to pumping or fluid injection are also integrated with the software on the laptop computer to estimate hydraulic properties of the test interval in real time.

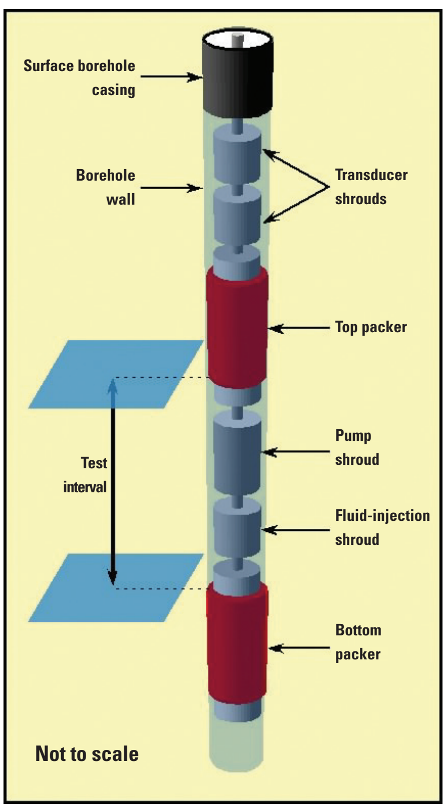

Figure 3. This diagram illustrates the Multifunction BAT³ in a bedrock borehole with borehole packers inflated to seal against the borehole wall. The transducer shrouds house the fluid-pressure transducers, the pump shroud houses the submersible pump, and the fluid-injection shroud houses a fluid-injection valve. Not shown in the diagram are the transducer wires, electrical wires and tubing that extend up the borehole to land surface and control the operation of the downhole equipment. The length of the test interval is adjusted by adding additional sections of pipe between the fluid-injection shroud and the bottom packer. The equipment is lowered or raised in the borehole using steel pipe or a cable attached above the transducer shrouds.

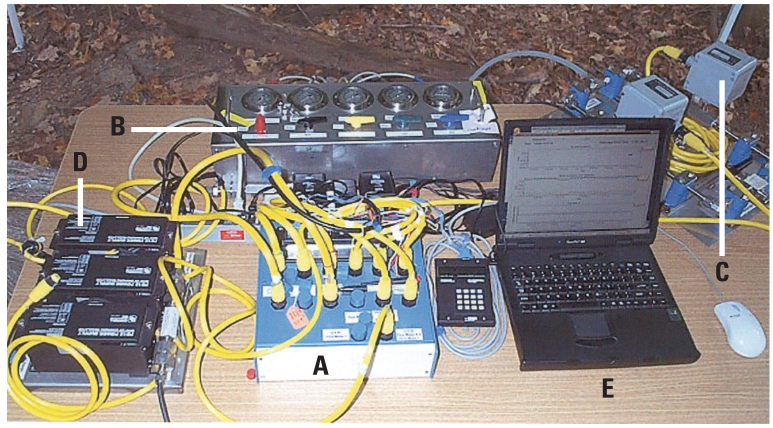

Figure 4. Data-acquisition and downhole controls for the Multifunction BAT³ include (A) data-acquisition panel, (B) pressure manifold to control downhole equipment, (C) flow meters, (D) battery panel, (E) laptop computer for real-time data acquisition, data display and interpretation.

The downhole equipment of the Multifunction BAT³ is designed for easy and rapid assembly with a test interval that can be adjusted to accommodate different borehole conditions. The downhole and data-acquisition equipment is designed to fit in a series of crates that can be shipped by overnight carriers. The downhole equipment can be lowered down a borehole using steel pipe, or a cable and winch.

Prototypes of the Multifunction BAT³ have been developed for applications in 4- and 6-inch (10.1 - and 15.2-centimeter) diameter boreholes and have been used to characterize fractured rock for water-supply and ground-water contamination projects, including the characterization of hydraulic properties and collection of water samples at sites of ground-water contamination by dense non-aqueous phase liquids (DNAPLs).

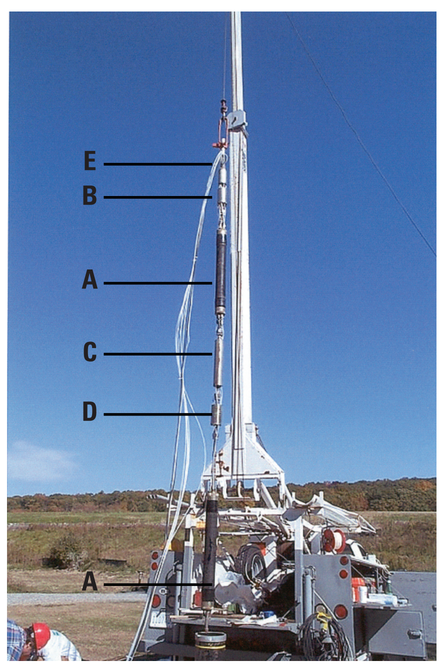

Figure 5. A prototype of the multifunction BAT³ supported from truck-mounted winch as it is being prepared for installation in a borehole. Shown in the photograph are (A) inflatable packers, (B) transducer shrouds, (C) pump shroud, and (D) fluid-injection shroud. Tubing and wires (E) used to control the downhole equipment extend from the transducer shrouds. In this configuration of the Multifunction BAT³, pipe has been added in the test interval to extend the test interval to approximately 8 feet; the minimum length of the test interval in this configuration is approximately 5 feet.

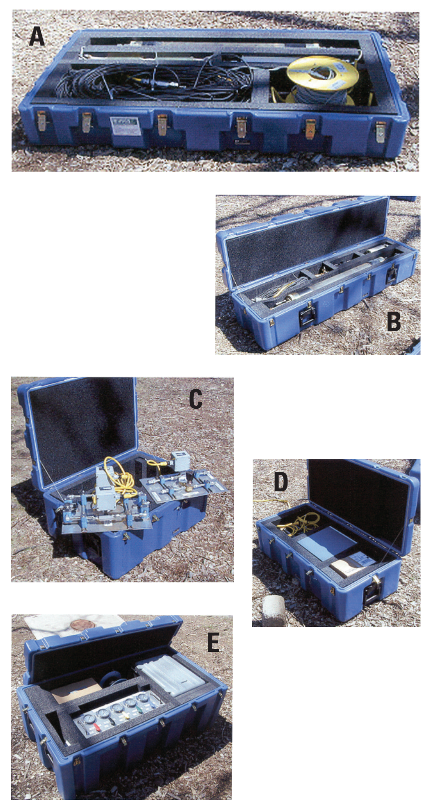

Figure 6. The prototype of the data-acquisition and downhole components of the Multifunction BAT³ is designed to fit in five shipping crates: (A) top packer, transducers and submersible pump, (B) bottom packer, (C) flow meters, (D) data-acquisition equipment, (E) controls for downhole components.

Characterizing Hydraulic Properties of Fractures

Sections of a borehole containing highly transmissive fractures are most easily tested by withdrawing water, whereas fractures with low transmissivity are tested by injecting small volumes of fluid. The Multifunction BAT^3 is configured with both a submersible pump and a fluid-injection apparatus in the test interval to accommodate hydraulic tests that either withdraw or inject water. With this capability, the Multifunction BAT^3 can estimate transmissivity ranging over approximately 8 orders of magnitude.

Hydraulic tests conducted on isolated sections of the borehole can be interpreted to provide a profile of transmissivity as a function of depth in the borehole. The transmissivity profile can be used in conjunction with other site information to develop an understanding of the controls on fluid movement and chemical transport in fractures (Shapiro and others, 1999), for example, transmissivity can be correlated with the orientation of fractures, rock type, depth and other physical and geologic factors. In addition, the transmissivity can be used to quantify the volume of fluid moving through fractures in the aquifer (Hsieh and Shapiro, 1996).

Collecting Water Samples for Chemical Analyses

In open boreholes intersected by multiple fractures, the contribution of water from fractures to the pump discharge is weighted according to the transmissivity of the fractures, regardless of the location of the pump intake. This results in an integrated water sample that is biased to the chemical signature of those fractures with the highest transmissivity. Integrated concentrations may be appropriate in assessing the quality of domestic and public supply wells, but they are not useful in delineating the spatial distribution of contaminated ground water, or understanding the natural variability in ground-water chemistry.

The Multifunction BAT^3 isolates a short interval of the borehole and reduces the volume of water necessary to purge from the borehole prior to obtaining a water sample that is representative of the fluid

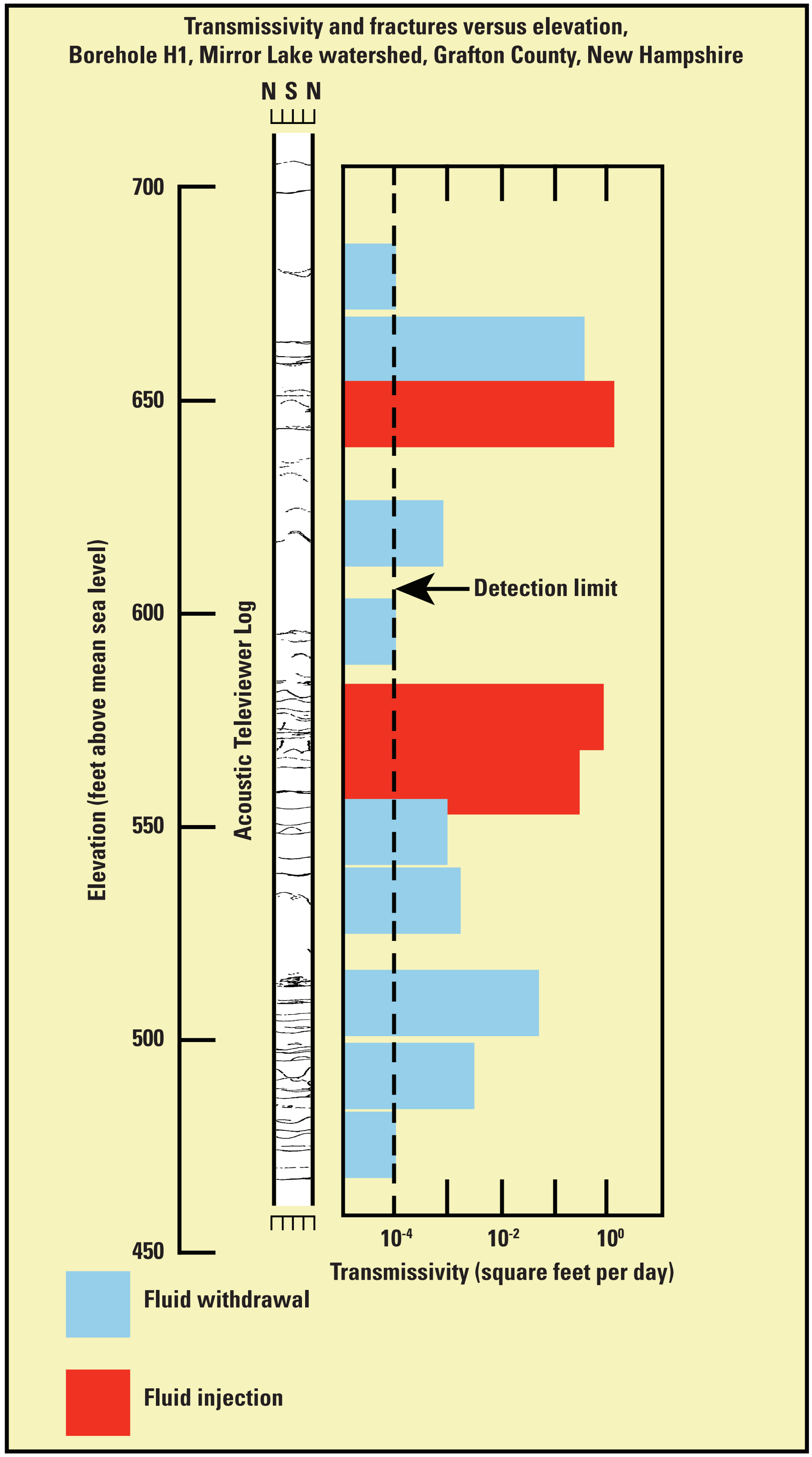

Figure 7. The open and oriented view of fractures on the borehole wall is interpreted from acoustic televiewer log conducted in the borehole (see, for example, Williams and Lane, 1998). The transmissivity of sections of the borehole containing fractures is estimated by either injecting or withdrawing fluid, and the length of the test interval is shown as the thickness of the tested section. The transmissivity of the test interval is determined by assuming steady-state radial flow (Shapiro and Hsieh, 1998); other interpretations of the measured fluid-pressure responses can also be applied. The transmissivity of the tested intervals varies over more than 4 orders of magnitude above the detection limit of the equipment. The detection limit for the transmissivity using the prototype of the Multifunction BAT^3 is approximately 10^{-4} square feet per day (~10^{-10} square meters per second), which is dictated by the sensitivity of the flow meter used to monitor fluid injection rates; the lower limit of the flow meter used in the current configuration of the Multifunction BAT^3 is approximately 9 x 10^{-4} gallons per minute (~3.4 x 10^{-3} liters per minute). The maximum transmissivity that can be estimated is dependent on the capacity of the submersible pump.

in the fractures, rather than the borehole fluid. Pressure transducers monitoring fluid-pressure responses above and below the test interval ensure that fluid is being withdrawn from the test interval. The submersible pump in the prototype of the Multifunction BAT[3] can achieve flow rates as low as 0.026 gallon per minute (0.1 liter per minute) to accommodate low-flow sampling protocols (Puls and Barcelona, 1996).

Dichlorodifluoromethane (CFC-12) concentrations in ground water collected from Borehole H1, Mirror Lake wastershed, Grafton County, New Hampshire

Test Type	Test Interval (feet above mean sea level)	CFC-12 Concentration (picograms per kilogram water)
Open borehole	684.4 - 459.0*	163.2
Multifunction BAT[3]	656.8 - 641.7	91.2
Multifunction BAT[3]	585.6 - 570.9	73.3

*Denotes saturated section of the open borehole. The open borehole is 732.0 - 459.0 feet above mean sea level; the water level in the borehole is below the bottom of the borehole casing.

Table 1. Chlorofluorocarbons (CFCs), such as CFC-12, are synthetic gases that are released in the atmosphere from manufacturing. The historical record of CFCs in the atmosphere and their concentration in ground-water recharge is used to determine ground-water residence times (Busenberg and Plummer, 1992). Water samples were collected from borehole H1 (see figure 7 for the description of fracturing and transmissivity in the borehole) and analyzed for CFC-12. Samples were collected in borehole H1 by pumping from the open borehole and by hydraulically isolating intervals of the borehole using borehole packers. Chemical field parameters, such as pH, temperature, specific conductance, and dissolved oxygen, were allowed to stabilize in the pump discharge prior to collecting water samples. The CFC-12 concentration of water in the open borehole prior to pumping was most likely near the atmospheric equilibrium CFC-12 concentration at the time of sampling (approximately 323 picograms per kilogram). The water sample collected from the open borehole is most likely a mixture of water in the borehole and water drawn from various fractures. The CFC-12 concentrations taken by isolating discrete intervals in the borehole are appreciably less than the CFC-12 concentration of water withdrawn from the open borehole. The water samples collected by isolating discrete intervals of the borehole are more indicative of the water in the aquifer than the integrated water sample collected from the open borehole.

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More information about characterizing fluid movement and chemical transport in fractured rock aquifers can be found at the following web sites:

U.S. Geological Survey, National Research Program, Transport Phenomena in Fractured Rock: *http://water.usgs.gov/nrp/proj.bib/shapiro.html*

Ground-Water Flow and Transport in Fractured Rock, Mirror Lake, New Hampshire: *http://toxics.usgs.gov/sites/mirror_page.html*

The Fate of DNAPL in Fractured Rocks, Naval Air Warfare Center Research Site, Trenton, New Jersey: *http://toxics.usgs.gov/nawc_page.html*

U.S. Geological Survey, Office of Ground Water, Branch of Geophysical Applications and Support: *http://water.usgs.gov/ogw/bgas.*

Additional information on the fate and transport of toxic substances in the environment can be obtained at the U.S. Geological Survey Toxic Substances Hydrology Program web site: *http://toxics.usgs.gov.*

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