

Borehole-Radar Methods: Tools for Characterization of Fractured Rock

Introduction

Locating and characterizing bedrock fractures and lithologic changes is an important component of studies of ground-water supply and contamination in fractured-rock aquifers. Borehole-radar reflection methods provide information on the location, orientation, and lateral extent of fracture zones that intersect the borehole, and can identify fractures in the rock surrounding the borehole that are not penetrated by drilling. Cross-hole radar logging provides cross-sectional maps of the electromagnetic properties of bedrock between boreholes that can identify fracture zones and lithologic changes and can also be used to monitor tracer tests.

Borehole-radar logs can be integrated with results of surface-geophysical surveys and other borehole-geophysical logs, such as acoustic or optical televiewer and flowmeter, to distinguish transmissive fractures from lithologic variations or closed fractures. Integrated interpretation procedures provide results that can be used to develop conceptual and numerical models, design monitoring and sampling programs, and monitor implementation of contamination remediation measures, such as blast-fracturing.

Theory of Operation

Borehole-radar methods use the reflection and transmission of

radar-frequency electromagnetic (EM) waves to detect variations in subsurface properties. Borehole radar waves have frequencies of about 10 to 1,000 megahertz (MHz), with corresponding wavelengths in earth materials of meters to centimeters.

The principles of borehole-radar reflection logging are similar to those of surface-radar profiling, except that the antennas are connected together and lowered as a single unit down the open or polyvinyl chloride-cased borehole (fig. 1). A radar pulse is transmitted into the bedrock surrounding the borehole. The transmitted pulse moves away from the borehole until it encounters material with different electromagnetic properties, such as a fracture zone, change in rock-

type, or void. At this location, some of the energy in the radar pulse is reflected back towards the receiver, and some of it is transmitted further into the rock (fig. 1). A radar reflection profile along the borehole is created by taking a radar scan at each position as the antennas are moved in 0.1 to 1.0 meter (m) steps up or down the borehole. The typical reflection patterns observed in radar reflection profiles from planar and point reflectors are shown in figure 1.

Radar-reflection logging can be conducted with omni-directional or directional receiving antennas. Omni-directional antennas are useful for rapidly identifying the location, dip, and lateral continuity of fracture zones, but directional antennas are required to determine

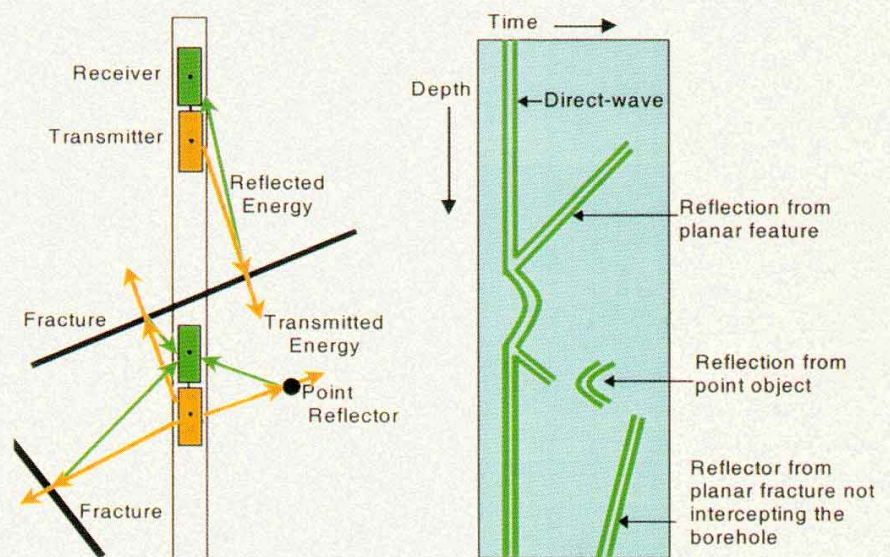


Figure 1. Orientation of transmitter and receiver in a single borehole and the resultant radar record from a fracture and a point reflector.

the strike of planar reflectors or the azimuth to point reflectors. Because directional antennas are less efficient than omni-directional antennas, and cannot “see” as far into the surrounding rock as the omni-directional antennas, logging runs that use both omni- and directional receivers are often conducted.

Cross-hole tomography is the process by which a two-dimensional model of physical properties in the plane between two boreholes is made. For tomography surveys, the transmitter antenna is in one borehole, and the receiver antenna is in the other borehole. Numerous radar scans are made for each transmitter position by moving the receiver along the borehole at regular intervals. A typical cross-hole scanning geometry is shown in figure 2. Hundreds or thousands of different combinations of transmitter and receiver locations are required for a tomography survey. For each scan, the travel-time and amplitude of a radar pulse as it travels from the transmitting antenna to the receiving antenna is measured. These data are used to create tomograms that map the radar propagation velocity and attenuation properties of bedrock

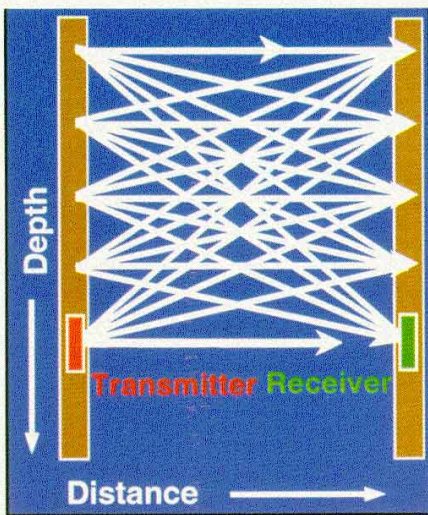


Figure 2. Ray coverage of cross-hole tomography.

between two boreholes. Variations in velocity and attenuation can be interpreted to identify fracture zones, lithologic contacts, and voids in the image plane.

Limitations and Conditions for Use

The use of borehole-radar methods is limited by subsurface conditions and available equipment. The radial distances that can be penetrated and the scale of structures that can be resolved depend on the electromagnetic properties of the rock and ground water, and on the frequency range and output power of the radar system and antennas.

EM radar-wave penetration distances are primarily controlled by the electrical conductivity of the medium through which the radar waves propagate. In electrically conductive rocks, such as shale or mudstone, or in geologic materials that contain saline water or mineralogic clay, EM waves may penetrate less than a meter. In electrically resistive rocks, such as granite or gneiss, EM waves may penetrate tens of meters.

The effect of the radar antenna frequency on radial penetration and resolution is shown in figure 3. The higher frequency antennas provide a more detailed image than the lower frequency antennas; however, the lower frequency antennas provide greater penetration.

Case Studies

Borehole-radar tomography and reflection logging have been successfully used to delineate and characterize permeable fractures (Olsson and others, 1992), monitor tracer tests (Lane and others, 1998; Lane and others, 1999), and monitor implementation of remedial measures, such as blast-fracturing (Lane, Haeni, Soloyanis, and others, 1996). Borehole-radar tomography has also been used with saline tracer

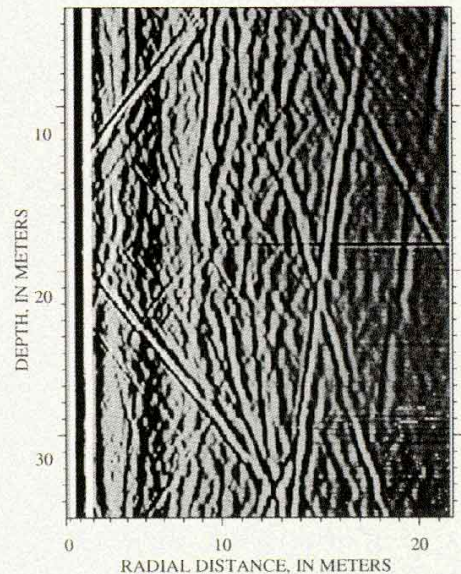
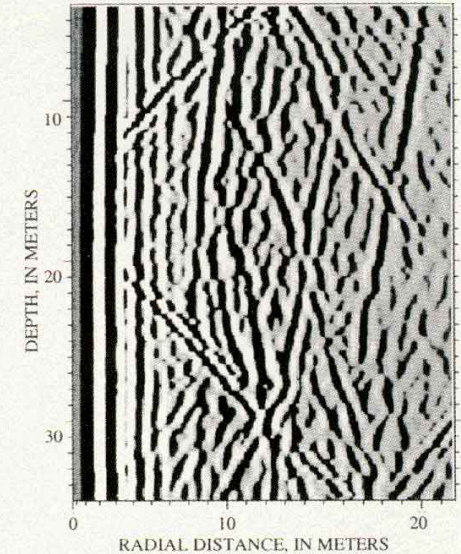


Figure 3. Borehole-radar logs showing planar features using 60-megahertz (MHz) antennas (above) and higher frequency 100-MHz antennas (below).

tests to image ground-water flow paths between boreholes.

Belvidere, Illinois

Conventional velocity and attenuation tomograms can be interpreted to identify rock properties, such as fracture zones and lithologic changes, but interpretation of the hydraulic properties is difficult. Attenuation-difference tomography with the use of saline tracers is one way to identify transmissive zones and ground-water flow paths because

salt water absorbs more radar energy than fresh water. Transmissive zones are identified by comparing tomographic data collected before the tracer test with data collected after tracer injection.

Radar tomography was used to monitor a saline tracer test in sedimentary rocks at Belvidere, Ill. (Lane and others, 1998). After two hydraulically conductive zones were identified using borehole geophysical logs, flowmeter logs, and straddle-packer testing, a saline tracer was injected into one of the permeable zones. The use of attenuation-difference tomography showed an increase in attenuation in the image plane after the saline-tracer injection that propagated between the boreholes with time (fig. 4).

Mirror Lake, New Hampshire
Attenuation-difference tomography can be used to monitor the movement of saline tracers through fractures across the plane between

boreholes by using suitable tracer-injection and radar-acquisition procedures. Time-lapse, attenuation-difference tomography methods were developed at the U.S. Geological Survey Fractured Rock Hydrology Test Site, Mirror Lake, New Hampshire to monitor saline tracer tests in fractured rocks (Lane, Haeni, Placzek, and Wright, 1996; Lane and others, 1999). Because the time required to acquire a single radar-tomography survey is generally longer than the time required to achieve tracer breakthrough and peak-concentration arrival at the pumped borehole, multiple tracer injections were used to capture the movement of the tracer across the image plane.

The borehole arrangement and data-acquisition procedure used for the experiment are shown in figures 5 and 6. A series of time-lapse images that track the movement of the saline tracer through fractures that cross the image plane are shown in figure 7. Measured radar-

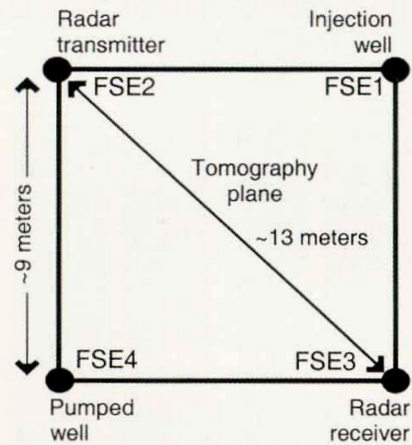


Figure 5. Plan view of FSE1 to FSE4 borehole cluster, FSE well field, Mirror Lake, Grafton County, New Hampshire.

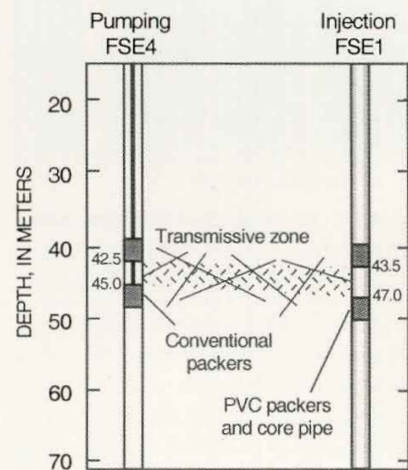


Figure 6. Arrangement of polyvinyl chloride (PVC) and conventional straddle packers in boreholes FSE1 and FSE4, Mirror Lake, Grafton County, New Hampshire.

attenuation differences correspond closely with the chloride concentration at the pumped well (fig. 8).

Loring, Maine

Borehole-radar methods were integrated with surface-geophysical surveys and other borehole-geophysical logging at a site in Loring, Maine to monitor the effects of blast fracturing an on-site recovery trench in a fractured limestone aquifer that was contaminated by petroleum products (Lane, Haeni, Soloyanis,

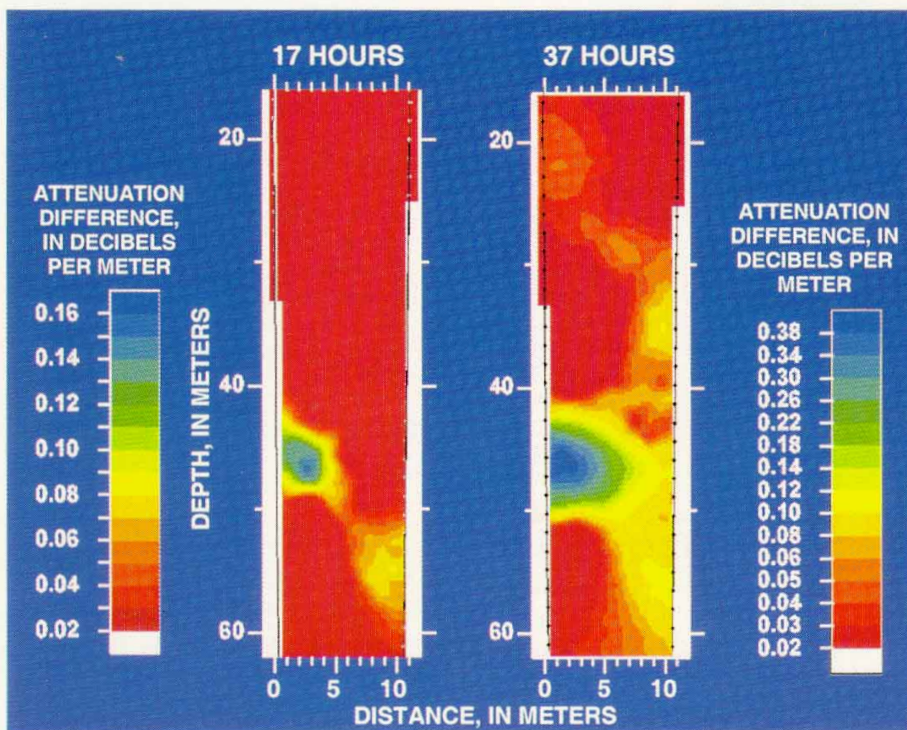


Figure 4. Sixty-megahertz borehole-radar attenuation-difference tomograms collected between two boreholes, Belvidere, Illinois.

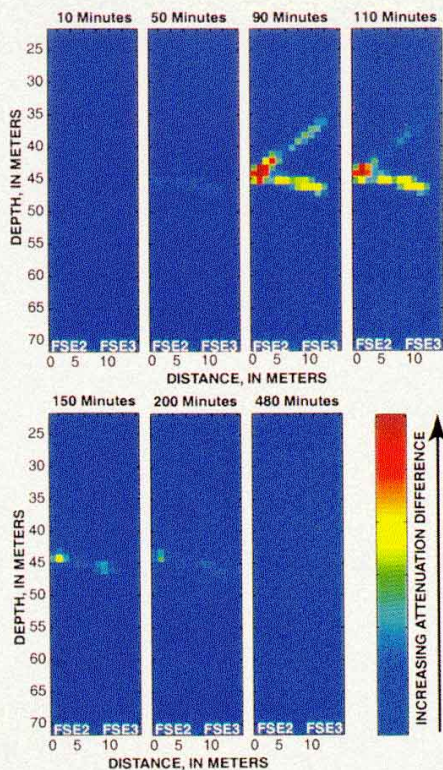


Figure 7. Time-lapse 100-megahertz attenuation-difference tomograms between FSE2 and FSE3 produced by using a sequential injection and incremental scanning method, Mirror Lake, Grafton County, New Hampshire.

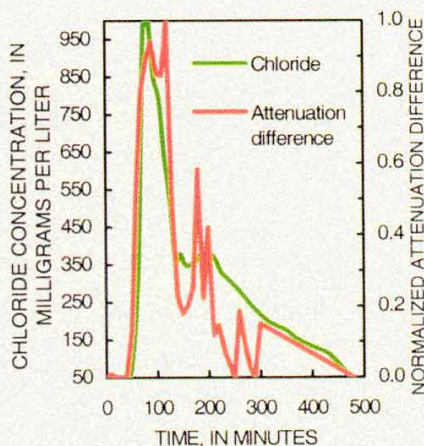


Figure 8. Chloride concentration in FSE4 and integrated radar attenuation difference in the FSE2 to FSE3 plane normalized to maximum and minimum values versus time, Mirror Lake, Grafton County, New Hampshire.

and others, 1996). Interpretation of the surface- and borehole-geophysical data showed that the blasting created an intensely fractured zone about 3-m wide, 50-m long, and 26-m deep. Cross-hole radar-velocity logs from a pair of boreholes that straddled the blasting zone are shown in figure 9. The logs show a decrease in radar velocity in the saturated zone after blast fracturing that outlines the depths affected by blasting. Before blasting, the secondary porosity of the bedrock was estimated at about 1 percent. Analysis of the radar-velocity logs indicates that the secondary porosity in the middle of the trench increased to more than 10 percent after blasting.

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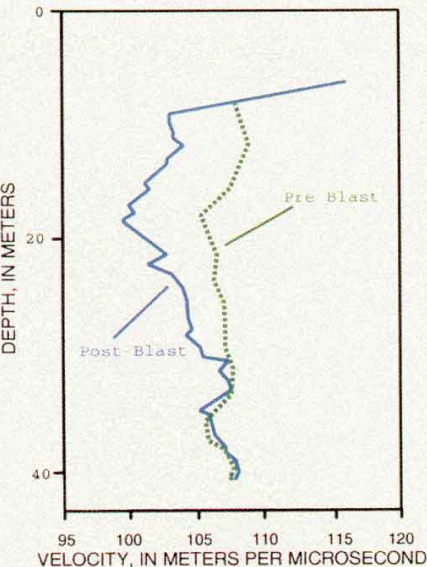


Figure 9. Horizontal level-run 22-megahertz cross-hole radar velocity plotted against depth between two test wells located across and perpendicular to trench axis, Loring, Maine.

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