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

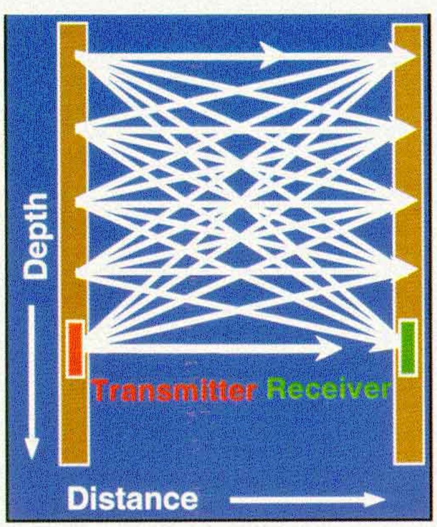

Figure 2. Ray coverage of cross-hole tomography.

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

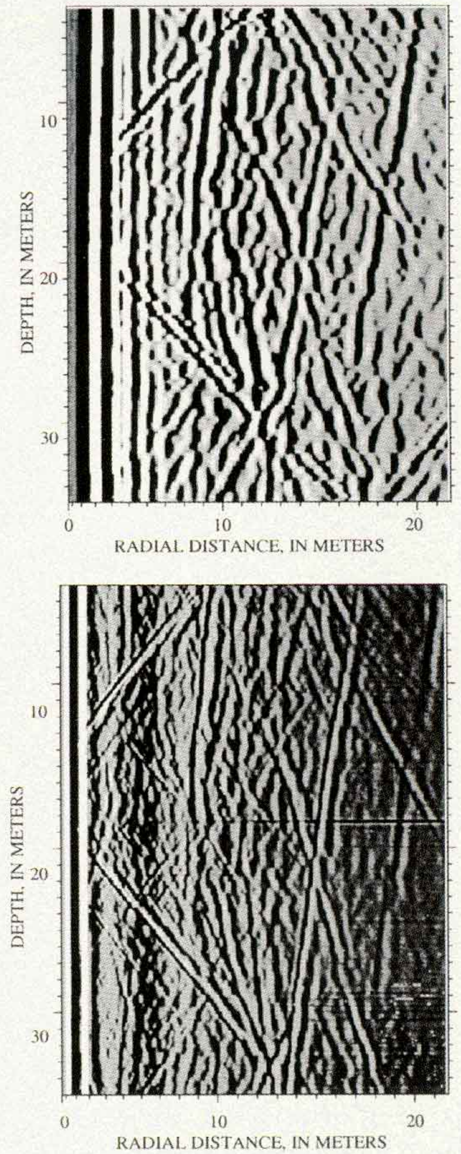

Figure 3. Borehole-radar logs showing planar features using 60-megahertz (MHz) antennas (above) and higher frequency 100-MHz antennas (below).

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