

Advances in Borehole Geophysics for Ground-Water Investigations

Detailed information on subsurface conditions is essential for the development and management of ground-water resources and the characterization and remediation of contaminated sites. Borehole geophysics provides a highly efficient means for the collection of such information. Recent advances in methods and equipment have greatly increased the ability of geoscientists to obtain subsurface information in ground-water investigations through the use of borehole-geophysical techniques.

Portable geophysical loggers that are specifically designed for ground-water applications (fig. 1) are now available. The geophysical loggers are PC-based and have menu-driven software for the collection, real-time display, and subsequent analysis of digital log data. Drawworks for shallow investigations are highly portable, and some have plastic-coated logging cables for easy decontamination. Logging probes are available that can be used in boreholes with a diameter as small as 5 centimeters. Many probes are capable of collecting multiple parameters with a single logging run, thereby greatly increasing the efficiency of the logging operation and taking full advantage of the synergistic nature of geophysical log data.



Figure 1. A PC-based geophysical logger with portable drawworks and plastic-coated logging cable in use at a contaminated ground-water site.

Electromagnetic-induction logging replaced normal-resistivity logging in the oil industry many years ago. Induction probes recently have been designed for small-diameter monitoring wells. Induction logs can be collected in water-, air-, and mud-filled holes and through PVC casing. Major factors that affect induction-log response in sand-and-gravel aquifers are the concentration of dissolved solids in the ground water and the silt and clay content of the aquifer. Induction logs, which are commonly run in combination with gamma logs, can be used to identify lithology and zones of electrically conductive contamination such as landfill leachate (fig. 2) and saltwater intrusion.

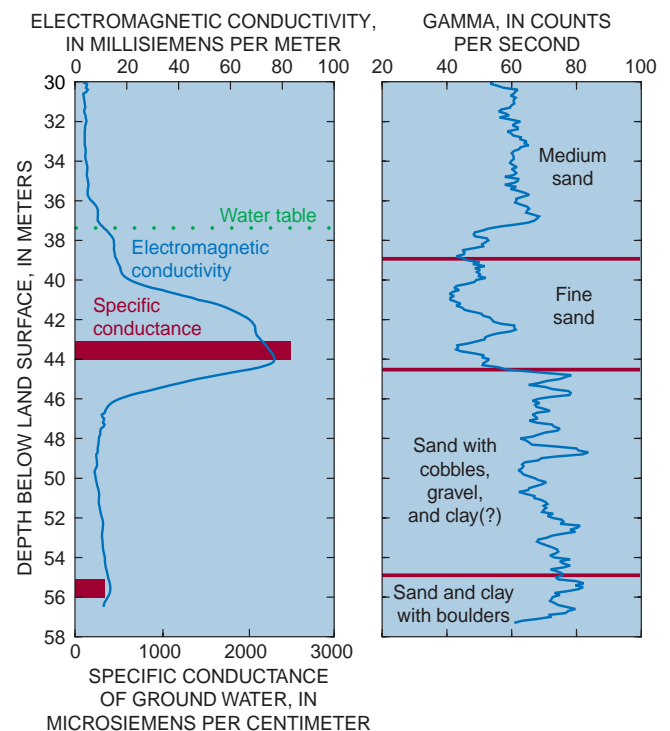


Figure 2. Electromagnetic-induction log delineates a leachate plume in a sand-and-gravel aquifer downgradient of a municipal landfill. The most highly contaminated part of the plume is at a depth of 41 to 45 meters (Williams and others, 1993).

High-resolution flowmeters that use heat-pulse and electromagnetic methods can measure extremely low vertical flow rates in boreholes. Conventional impeller flowmeters that are widely used in ground-water studies have a lower measurement limit of about 2 meters per minute, whereas the high-resolution flowmeters have lower measurement limits of less than 0.03 meters per minute. Flowmeters can be used to measure borehole flow under ambient as well as pumped conditions. Borehole-flow measurements made under ambient conditions can help to delineate transmissive fractures and other permeable zones (fig. 3) and to indicate the direction of vertical hydraulic gradients; they also are useful in interpreting fluid-conductivity logs and borehole water-quality data. Borehole-flow measurements made under pumped conditions can be used to develop hydraulic-conductivity profiles of aquifers.

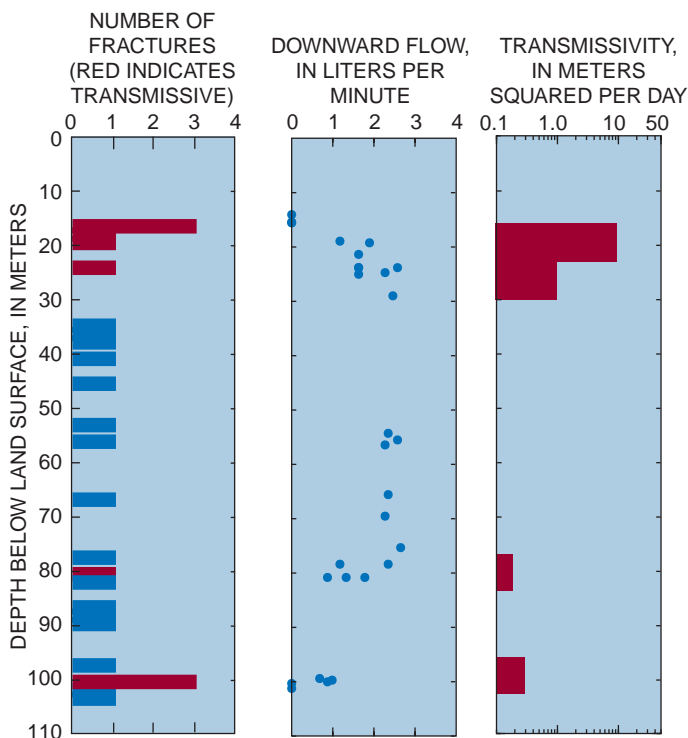


Figure 3.—Heat-pulse flow measurements indicate transmissive fracture zones in crystalline bedrock. Fracture distribution was determined from an acoustic-televiwer log and transmissivity was estimated from straddle-packer pump tests (Williams and Conger, 1990).

Television cameras commonly are used in ground-water studies to inspect the condition of well casing and screens; they also can be used in open bedrock wells to directly view (1) lithologic texture, grain size, and color; (2) water levels and cascading water; and (3) fractures. Television logs can be obtained in clear water and above the water level. The most sophisticated television systems are magnetically oriented, provide a 360-degree digital image of the borehole wall (fig. 4), and allow interactive determination of fracture and bedding orientation.

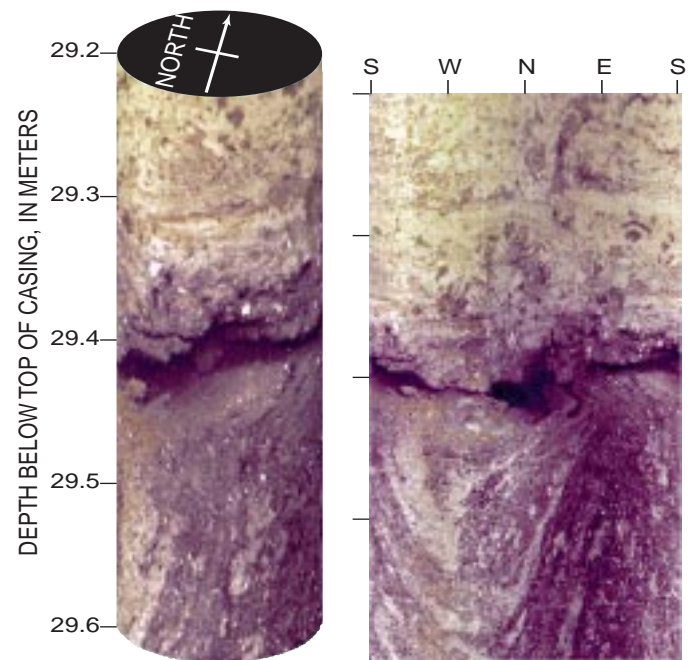


Figure 4.—"Virtual core" wrapped (left) and unwrapped (right) images of a bedrock fracture at a depth of 29.4 meters collected with a digital television camera. The images show that the fracture is at the contact between pegmatite and gneiss.

Acoustic televiwers provide a magnetically oriented, 360-degree, photographlike image of the acoustic reflectivity of the borehole wall (fig. 5). Televiwers have been used in the oil industry for many years and are being used increasingly in ground-water applications. Televiwer logs, which indicate acoustic transit time and reflected amplitude, can be obtained from water- or mud-filled holes. The newest digital televiwer systems allow interactive determination of fracture and bedding orientation (fig. 6).

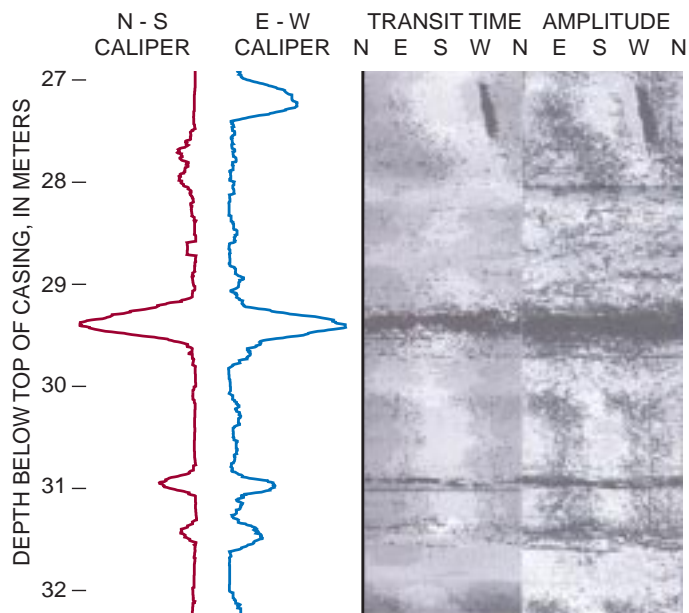


Figure 5.—Acoustic caliper, transit time, and amplitude logs collected with a digital televiwer. The bedrock fracture at 29.4 meters is indicated by increased travel time and decreased amplitude of the acoustic signal. The north-south and east-west calipers calculated from the acoustic transit time show an enlargement of the borehole at the fracture. This fracture zone produced most of the well yield, as indicated by heat-pulse flowmeter measurements under pumped conditions.

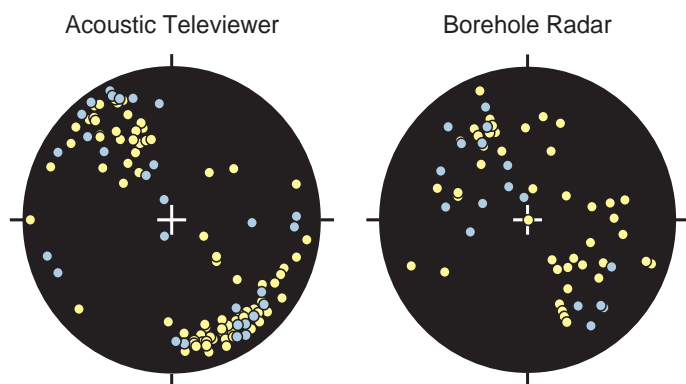


Figure 6.—Fracture orientation in limestone as determined from acoustic televiwer and borehole radar. Lower hemisphere equal-area projections of fracture poles reveal a conjugate set of northwest and southeast dipping fractures. Blue denotes that the fracture zone is transmissive, as indicated by heat-pulse flowmeter measurements (Lane and others, 1996).

Borehole radar provides a method to detect fracture zones at distances as far as 30 meters or more from the borehole in electrically resistive rocks (fig. 7). Fracture zones with electrical properties that differ from the surrounding nonfractured rock are excellent radar reflectors. Borehole radar has been successfully applied in granite, gneiss, and other crystalline rocks as well as in limestone and dolomite. Radar measurements can be made in a single borehole (transmitter and receiver in same borehole) or by cross-hole tomography (transmitter and receiver in separate boreholes). Single-hole, directional radar can be used to identify the location and orientation of fracture zones (fig. 6). Cross-hole tomography including radar velocity and attenuation can be used to delineate fracture zones between boreholes. The movement of a saline tracer through fracture zones can also be monitored by borehole radar (fig. 8).

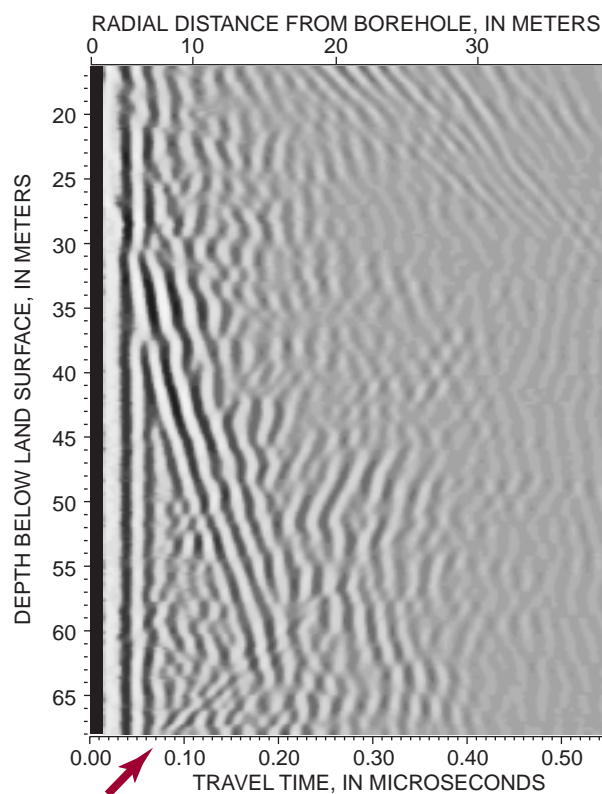


Figure 7.—Borehole radar detects fracture zones in granite. The radar reflector indicated by the arrow corresponds to a fracture zone that intersects the borehole at a depth of 75 meters. The fracture zone reportedly yielded more than 1,000 liters per minute (Lane and others, 1994).

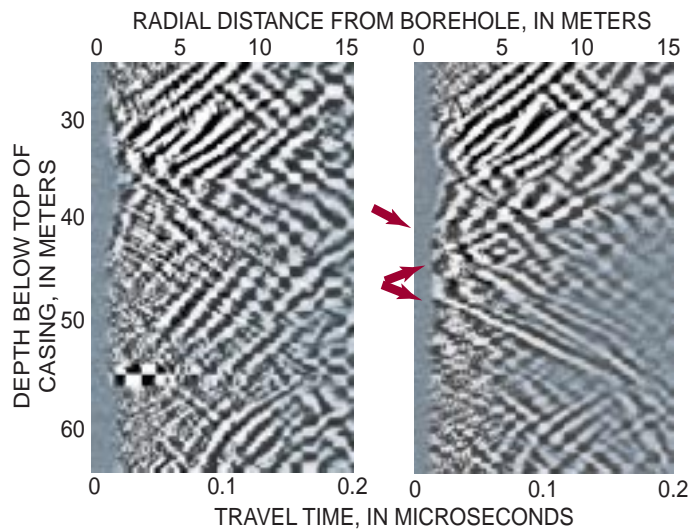


Figure 8.—Borehole radar before (left) and after (right) injection of saline tracer in crystalline bedrock. Fracture zones that intersect the well at 39 and 44 meters (indicated by arrows) are major pathways for movement of the saline tracer (Lane and others, 1996).

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