Appendix A—Methods of Characterization

A total of 29 methods were used by the USGS and the USEPA for the geologic and hydraulic characterization of the Galena-Platteville deposits in Illinois and Wisconsin (table 1). This discussion is meant to provide more information on the methods, the types of information they provide, and some of the limitations to their use (table 2) so that a better understanding of the study results can be obtained. A full discussion of each method is beyond the scope of this report and persons wishing to obtain a detailed understanding of each method are referred to the references cited in this appendix.

Background Information

Data from numerous background sources were used for the investigations of the Galena-Platteville aquifer and much of that data formed the foundation for the discussion on the geology and hydrology of the aquifer presented in the report. However, the utility of background information obviously is not restricted to investigations of the Galena-Platteville aquifer and a review of available geologic, hydrologic, topographic, and water-quality data will benefit any hydrogeologic investigation.

Federal and State Databases

A primary source for background hydrogeologic data is Federal and State databases. The most comprehensive Federal database used here is the USGS National Water Information System (NWIS). Geologic, hydrologic, and well-construction data can be found in the Ground-Water Site Inventory (GWSI) component of NWIS. Geologic data in GWSI includes lithology and thickness of rock units; hydrologic data include aquifers penetrated by the wells, water levels, and the hydraulic properties of the aquifer. Water-quality data can be found in the Water-Quality database (QWDATA) component of NWIS. NWIS data can be obtained from USGS offices or through the World Wide Web at *http://waterdata.usgs.gov/nwis/qw*. Extensive water-quality data also are available in the database, STORET, maintained by the USEPA. STORET data can be obtained through the World Wide Web at *http://www.epa.gov/STORET/* . Similar data also are available from various State-maintained databases.

Previous Studies

Previous studies and reference bibliographies for locations in and near planned areas of investigation are sources of valuable basic and interpreted hydrogeologic and water-quality data. Previous investigations generally fall into two categories, area and site specific. Area investigations typically present data from a large geographic area that includes or is near the site of interest. Area investigations are best suited for development of conceptual models and to plan initial data collection. Previous site-specific investigations typically are used to identify gaps in the understanding of hydrogeologic or chemical conditions at a site.

The types of previous investigations and availability of information is variable. Reports pertaining to investigations performed by the USGS or State scientific surveys can be identified with comparative ease by a reference search. For example, Brown and others (1997) compiled the listing of readily available reports pertaining to the geology, hydrology, and water quality of the Galena-Platteville deposits in the subcrop area. Investigations performed by the USGS and State scientific surveys typically are available readily from the agencies and university libraries. Reports prepared by or for the USEPA or State environmental protection agencies, such as for Superfund sites, generally are public documents, but their distribution typically is limited and their availability usually is not widely known. Reports prepared by other Federal and State agencies, such as a State department of transportation, usually have similar distribution limitations and these reports may need to be requested specifically from the agency. For example, investigations regarding leaking underground storage tank sites in Illinois only can be accessed through a Freedom of Information Act request. Another valuable source of background data is reports prepared by private geotechnical firms for corporate clients. However, these reports commonly are not publicly available.

Analysis of Topographic Maps and Aerial Photographs

Large faults, inclined fractures, and zones of carbonate solution, in some cases, can be identified at land surface in aerial photographs and in topographic maps (Lattman and Matzke, 1961). The surficial expression of these features may provide information on their orientations, locations of preferential flow, anisotropy within the bedrock, and boundaries of ground-water-flow systems. Features may be visible as patterns of stream drainage or vegetation, for example. Potential for misidentification of anthropogenic features (such as hedge rows and power lines) as natural linear features requires that identified features be field verified.

Extensive subsurface solution of carbonate deposits can result in development of sinkholes and other karst features that can be identified on topographic maps and aerial photographs as dry or water-filled circular depressions and centripetal drainage patterns (drainage lines converge into a central depression). Development of sinkholes and other karstic features can be indicative of an extensive network of secondary-permeability features in the subsurface.

Because ground water typically discharges to surface-water bodies, ground water usually flows from areas of higher surface topography to areas of lower surface topography. As a consequence, analysis of surface topography and the location of surficial hydraulic features can provide a preliminary identification of the direction of ground-water flow. Areas of elevated surface topography usually correspond to areas of elevated bedrock topography, which may be associated with comparatively competent impermeable rock.

Topographic analysis is a potentially useful method for obtaining a preliminary indication of the permeability distribution and directions of preferential flow in the bedrock. This method is best suited for identification of large features in areas where glacial deposits are thin or absent.

Topographic maps at a scale of 1:24,000 and photographs at a scale of 1:12,000 can be obtained from the USGS through the World Wide Web at *http://geography.usgs.gov/www/products/1product.html*. Other topographic maps and aerial photographs also may be available from various Federal and State agencies, and private vendors.

Observations at Quarries and Outcrops

Quarry and outcrop exposures provide an opportunity for inspection of the lithologic composition, texture, bedding, secondary-permeability features (vugs, bedding-plane partings, faults, fractures), and weathering characteristics of the exposed deposits (fig. A1), which form the basis for their stratigraphy. The spacing, location, and orientation (strike and dip) of these features can be measured and the connectivity of the features estimated. Rock exposed in quarries can be affected by stress release, which produces fractures that are not indicative of in-situ conditions, potentially resulting in an inaccurate estimation of the density and orientation. Also, weathering, erosion, and vegetation growth potentially can obscure the presence and orientation of some features.

Hydrologic information also can be obtained from quarry and outcrop observations (fig. A1). Seeps along the face of quarries and outcrops can be used to locate preferential-flow paths associated with secondary-porosity features and geologic deposits (beds or larger stratigraphic units) that restrict vertical flow. If a quarry intersects the water table and the water is not withdrawn by pumping, the vertical position of the water table can be approximated.

Figure A1. Outcrop of Galena-Platteville deposits in northern Illinois. Photograph by Patrick Mills.

Surface Geophysics

Surface-geophysical methods can provide additional information on hydrogeologic conditions at a site prior to drilling. Surface-geophysical methods, such as square array resistivity and ground-penetrating radar, can provide a quick and inexpensive (in comparison to drilling) preliminary assessment of geologic conditions at a site, including the location and orientation of fractures and sinkholes. However, the utility of surface-geophysical methods is dependent highly on a contrast between the properties of the secondary-permeabilty feature and the surrounding geologic media, as well as the properties of the media between the feature and the land surface. This dependency limits the utility of surface-geophysical methods in the identification of small or deep secondary-permeability features, which may be important to flow and contaminant transport. In addition, surface-geophysical methods usually require data collection from boreholes or wells to verify interpretations. Surface-geophysical methods used to characterize the Galena-Platteville aquifer during these investigations were limited to square-array resistivity and ground-penetrating radar.

Square-Array Resistivity

Electrical resistivity is a physical property of rock and is dependent on a number of factors including lithology, porosity, degree of water saturation, and concentration of dissolved solids. Azimuthal square-array resistivity (SAR) measurements involve sending an electrical current into the earth and measuring changes in apparent rock resistivity to the electrical current with respect to orientation of electrodes and induced current paths. This measurement is done by rotating four electrodes arranged in a square about a center point in 15° increments for a total of 90°. The center point of the square is considered the measurement location and, as a rule of thumb, the side length is approximately equal to the depth of penetration. The array is expanded symmetrically about the center point, in defined increments so that the SAR data also can be interpreted as a function of depth.

Apparent resistivity is measured along perpendicular sides of each square and across the diagonals of each square. Changes in apparent resistivity with direction and depth are measured at a single location. The apparent resistivity data are plotted against the azimuth of that measurement and the principal fracture strike direction is perpendicular to the direction of maximum apparent resistivity (fig. A2).

Variations in resistivity readings can be caused by many factors such as slope of the bedrock surface, dip of bedding or foliation, and overburden thickness. The depth of penetration also is affected by the conductivity of subsurface materials—the more conductive the subsurface material the smaller the depth of penetration—and cultural interference such as overhead power lines and buried cables. To correctly interpret azimuthal resistivity data over fractured rock, the bedrock also must act as an anisotropic medium.

Surface Ground-Penetrating Radar

Ground-penetrating radar (GPR) is a high-frequency electromagnetic (EM) method that has been developed for shallow (typically less than 50 ft), high-resolution investigations of the subsurface. GPR can be used to map hydrogeologic conditions that include depth to bedrock, depth to the water table, depth and thickness of overburden, lithologic contacts, and the location of subsurface cavities and fractures in bedrock. Environmental applications of GPR include locating objects such as pipes, drums, tanks, and utilities; and mapping contaminants.

The GPR system pulses high frequency EM waves into the ground from the transmitting antenna (Annan, 1992, Daniels, 1989). When the transmitted radar energy encounters a subsurface feature with contrasting EM properties, a portion of the energy is reflected back to a receiving antenna and the remaining energy is transmitted downward to deeper material. As the antenna(s) are moved along a survey line, a series of scans are collected at discrete points along the line. These scans are positioned side by side to form a display profile of the subsurface. When GPR data are collected on closely spaced profiles (less than 3 ft), these data can be used to generate three-dimensional views of the subsurface.

The principle-limiting factor in depth of penetration of the GPR method is attenuation of the EM signal in the subsurface materials. Scattering of EM energy may become a dominant factor in attenuation if the subsurface is highly heterogeneous. GPR depth of penetration can be more than 100 ft in less conductive materials. However, penetration commonly is less than 30 ft in most soil and rock and can be less than 3 ft in clay and material with conductive pore fluid.

GPR provides the highest lateral and vertical resolution of any surface-geophysical method. Various frequency antennas (from 10 to 1,000 megahertz) can be selected so that the resulting data can be optimized to the projects needs. Lower frequency provides greater penetration with less resolution. Higher frequencies provide less penetration with higher resolution. Vertical resolution ranges from 1-2 in. to about 1 ft. Horizontal resolution is determined by the distance between station measurements, the sample rate, and the towing speed of the antennae.

GPR has been used to locate and characterize fractures and faults (Benson, 1995). The detectability of these features increases with the size of the feature and with the presence of distinctive pore fluids or conductive fill material. GPR can be used to detect subsurface features from less than an inch to 5 or more feet in size (Martinez and others, 1989).

Lithologic Logging of Wells

After a preliminary assessment has been performed through analysis of background information and, perhaps, collection of surface-geophysical data,

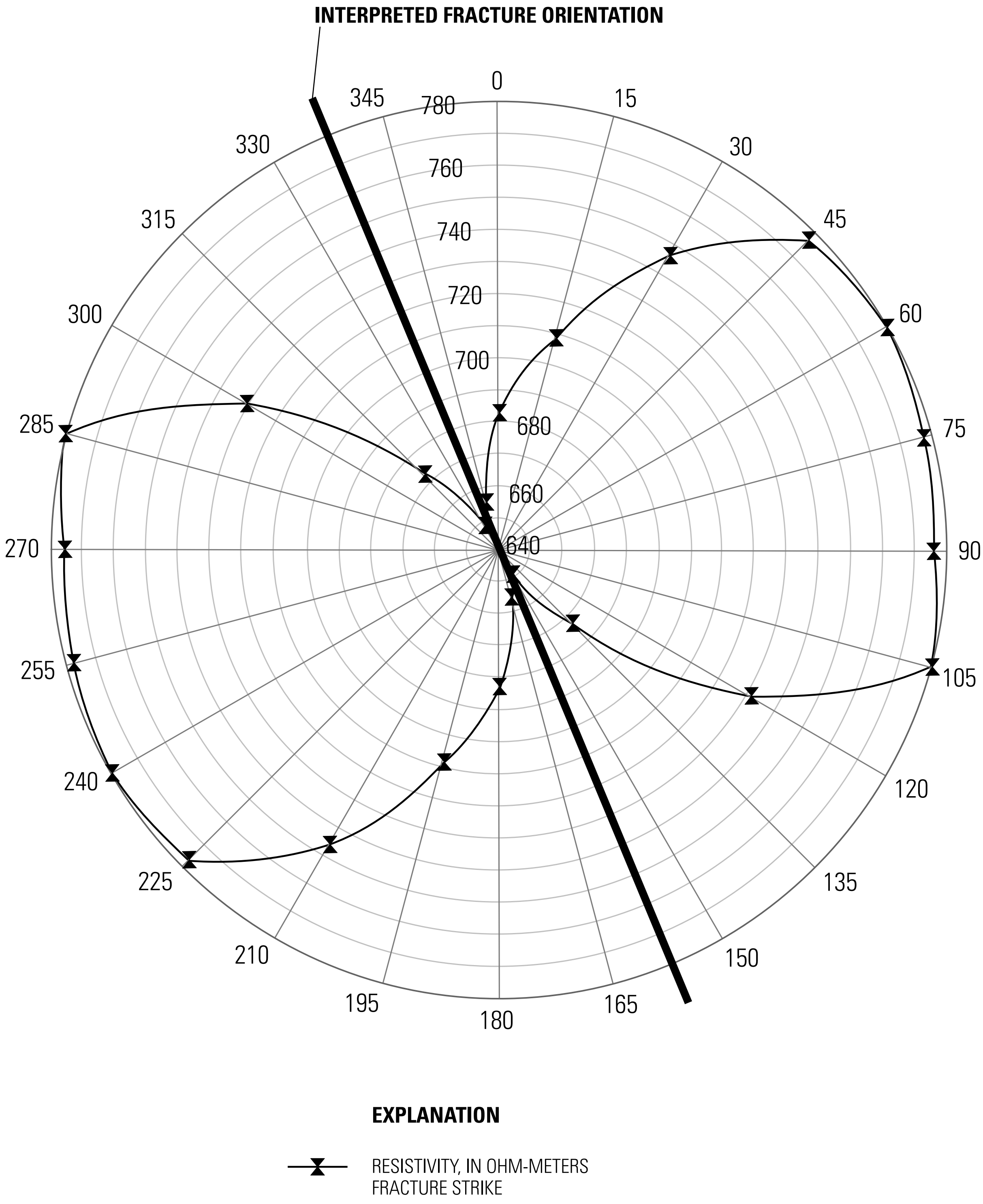


Figure A2. Example results of a square-array resistivity survey (223-foot square) at the Irene Road quarry site near Belvidere, Ill.

well drilling usually is the next step for hydrogeologic investigation. Description of the rock cuttings expelled from the borehole, as a function of depth during drilling, including lithology, presence or absence of fossils, mineralogy, weathering features, forms the primary basis for geologic interpretation at a site. Observation of the drilling speed and the amount of water ejected from the borehole also can provide important insight into the location of secondary-permeability features. For example, comparatively slow drilling rates associated with unweathered rock and minimal increases in the amount of water ejected from a borehole is indicative of competent, unfractured rock. A moderate increase in drilling rate associated with vuggy or weathered cuttings and a small increase in the amount of water ejected from the borehole can be indicative a vuggy deposits or zones of multiple fractures of low to moderate permeability. A sudden increase in drilling speed over an interval of a foot or less associated with an appreciable increase in the amount of water ejected from the borehole can be indicative of a permeable fracture. A sudden increase in drilling speed over an interval of a foot or less associated with argillaceous cuttings and no increase in the amount of water ejected from the borehole may indicate argillaceous deposits or fractures that have been infilled with clay minerals. A sudden increase in drilling speed coupled with the termination or a substantial decrease in the amount of water or cuttings ejected from the borehole may indicate a solution opening.

Identification of the geologic material ejected from the borehole and the depths of water-producing intervals is a standard part of the drilling and serves as the cornerstone of any hydrogeologic assessment. This information can be used to provide a preliminary assessment of the location of high, moderate, and low permeability features in the aquifer and the factors that may affect the permeability distribution. However, a thorough characterization of the hydrogeology of any aquifer, and particularly a fractured-rock aquifer, requires collection of more detailed data.

Core Analysis

Rock coring involves the extraction of (comparatively) undisturbed rock material and allows for its visual inspection. Core inspection can identify lithologic composition, texture, matrix porosity, bedding thickness, erosion and corrosion surfaces developed between depositional cycles, bedding-plane partings, and fractures (opened by stress release and dissolution). From this information, stratigraphy can be determined. Changes in color, such as iron staining, and mineralization (dolomitization), may represent past or present pathways of preferential flow of water and possibly recent contaminant transport. Rock samples obtained from coring can be tested for a variety of geotechnical properties, such as matrix porosity and permeability.

Cores allow detailed inspection of many features that cannot be observed in drill cuttings or are destroyed by the drilling process, making cores particularly useful for detailed analysis of in-situ geology. Cores can allow observation of many geologic features that also can be observed at quarries and outcrops, but because cores have limited spatial coverage, they typically don't provide information on large-scale features (such as vertical fractures) or the spatial variability of features. Laboratory analysis of core samples provides only point-scale information. Cores will not provide information on recent weathering of carbonate units; which for some of the Galena-Platteville deposits is necessary for accurate stratigraphic determination (Willman and Kolata, 1978; Mills and others, 2002a, b). Generally, cores should be greater than 3 in. in diameter for effective construction of a conventional 2-in.-diameter monitoring well in the resulting core hole. Cores should be no smaller than about 2 in. for reliable laboratory analysis of porosity. Collection of cores using angle drilling, as opposed to vertical drilling, will improve greatly the likelihood of encountering vertical and inclined fractures.

Core samples are expensive to obtain and commonly are broken in situ, making it difficult to determine the depth of certain features, particularly fractures, and whether or not the fractures are representative of in-situ conditions or created by the drilling process. As a consequence, limited coring is done in most investigations.

Geophysical Logging

Drilling and coring are the only means of providing direct access to an aquifer. Drilling and coring are expensive, and lithologic logging and core analysis can be subjective, depending on the skill, objectives, and resources of the person providing the description. In addition, drilling and coring gives information only on conditions in the immediate vicinity of the borehole. To maximize and standardize the information that can be obtained from the borehole, geophysical logging usually is performed. Geophysical logging involves continuous or point measurements of geophysical properties, either directly or indirectly, that can help identify geologic, hydraulic, or fluid properties within the borehole. Most geophysical logs convey data by means of a graph with depth scale (Y-axis) and the measured values (X-axis). The utility of the geophysical logs for lithologic and stratigraphic analysis is improved by comparison to detailed lithologic descriptions and results of geotechnical testing.

Natural Gamma

Natural-gamma logs record the amount of radiation emanating from naturally occurring radionuclides, including uranium, thorium, and potassium, in the rock. The amount of radiation emitted by most sedimentary rocks (including the Galena-Platteville dolomite) is related directly to its clay content. Natural-gamma logs can provide data concerning changes in the clay content, which can be related to lithology, stratigraphy, and the presence of clay infilling of fractures and solution openings (figs. 35, 40, A3). These features usually can be correlated across a site and are an important part of any hydrogeologic assessment.

A natural-gamma log can be used in cased or open boreholes, in the presence of clear or opaque fluids, and above or below the water column. The response of the natural-gamma log can be affected by the presence of clays in materials used for drilling or well sealing. The area of investigation is approximately a 1-ft radius from the center of the logging tool.

Spectral Gamma

A spectral gamma log is used to define the specific source (uranium-238, thorium-232, and potassium-40) of the natural-gamma radiation emanating from the geologic formation. By identifying the source of the radiation, some generalizations can be made about the clay mineralogy and the environment of deposition, which can be used to identify the presence of clay-infilled fractures or solution openings. For example, the uranium content in clay-infilled fractures usually is elevated in comparison to that of the bulk of the rock (Fertl, 1979; Fertl and Rieke, 1980). Spectral gamma logging requires measurements be taken at discrete depths in the borehole, rather than continuous profiling and typically can require up to 30 minutes to take a single measurement.

Three-Arm Caliper

The three-arm caliper is a mechanical device that records the inside diameter of the borehole (figs. 35, A3). Caliper tools are calibrated through objects of a known diameter and (depending on the tool) can be sensitive to changes as small as 0.15 in. This type of tool can be used in cased or open holes, in clear or opaque fluids, and above or below the water column. However, an open borehole is required for identification of secondary-permeability features.

Changes in borehole diameter identified with the caliper logs can be associated with a variety of features, including fractures, wash outs, cave ins, solution openings, vugs, well screens, well casing, and cracks in the casing. Caliper logs also can be used to locate intervals of competent rock for setting packers for aquifer and flowmeter tests. Because borehole diameter can affect the response of other geophysical logs, the caliper log also is useful in the analysis of other geophysical logs, including interpretation of flowmeter logs. Although caliper logs can identify variations in wellbore diameter associated with a variety of well construction and secondary-permeability features, it cannot uniquely identify the type of feature, its size, orientation, or if it is permeable. In addition, features with a small aperture at the borehole wall can produce a minimal response on the log.

Borehole Camera

A borehole camera essentially is a small television camera that takes video images of the borehole wall. These images can be viewed on a television monitor and recorded on video tape. Because no natural light is present in a borehole, these cameras have built-in light sources. Two camera lens options typically are available; one lens obtains a down hole view (vertical axis) and the second type of lens provides a horizontal view of the side of the borehole. The side view lens can be rotated 360 degrees to view the entire borehole.

Borehole-camera logs can identify the type and location of secondary-permeability features, depth to water, the presence of cascading water, areas of clear and turbid water, changes in borehole diameter, borehole smoothness or ruggosity, casing conditions, location of foreign objects, as well as identifying some permeable features. The camera can be used in or out of water. The image quality is dependent on water clarity and the tool provides poor results where sediment, algae, or iron flocculate result in opaque water. The camera logs used for the investigations described here could not determine the strike and dip of inclined fractures. Viewing and analysis of camera logs after the initial data collection occurs in real time, which can be time consuming in comparison to other types of logs.

Acoustic Televiewer

The acoustic-televiewer tool scans the borehole wall with an acoustic beam generated by a rotating, rapidly pulsed piezoelectric source as the tool is moved up or down the borehole and the amplitude and travel time of acoustic signals reflected from the wall are measured. A magnetic sensor is used to orient the images. A smooth and hard borehole wall produces a uniform acoustic reflection. The intersection of a fracture, vuggy interval, or solution feature with the borehole scatters the acoustic waves, producing a dark feature on the televiewer image, which can be identified (figs. 40, A3). Because the

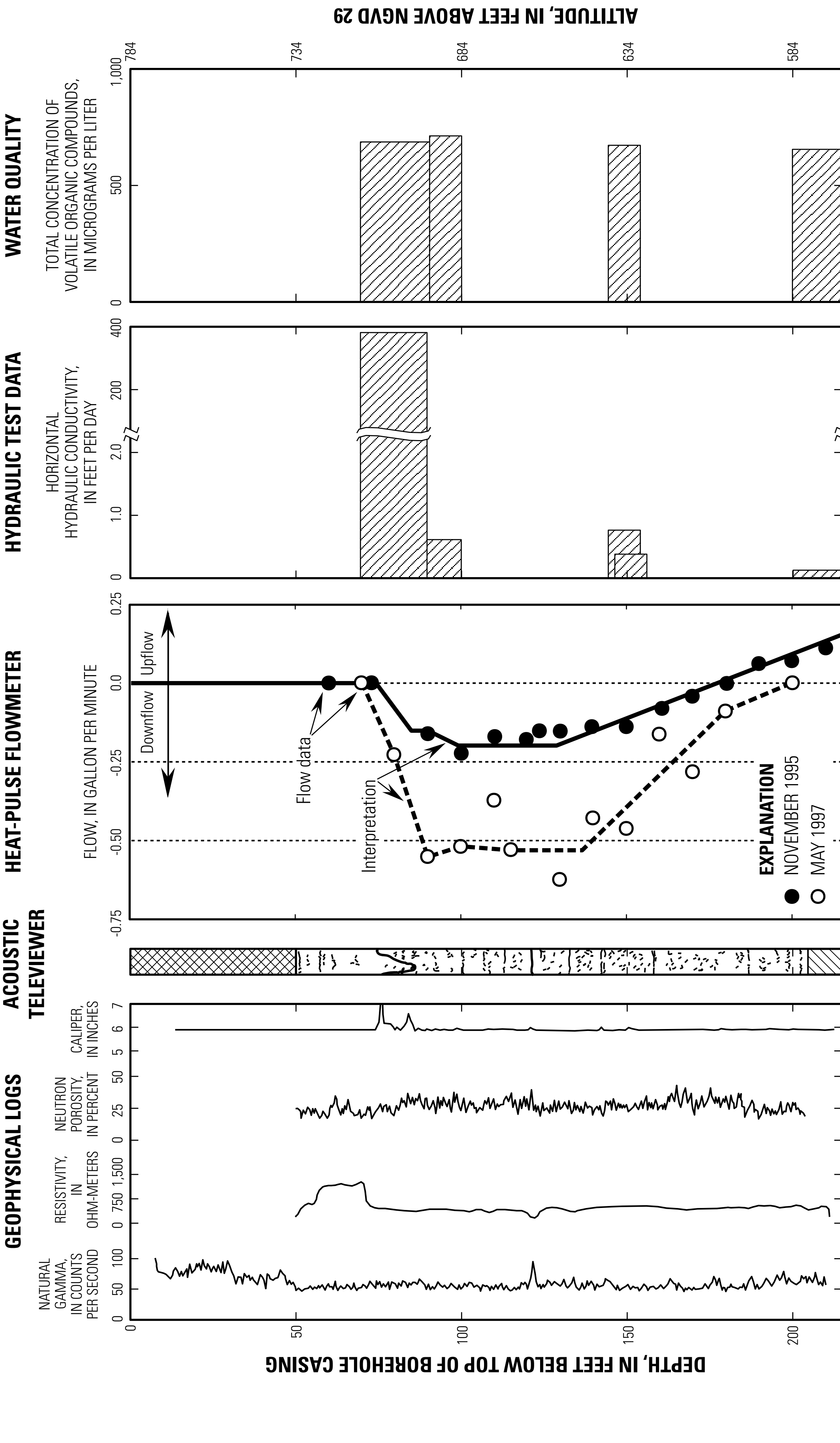


Figure A3. Stratigraphy, select geophysical logs, and horizontal-hydraulic-conductivity data for borehole T1 in Belvidere, Ill.

televiewer image is oriented magnetically, the orientation of the feature can be determined. The televiewer has an advantage over borehole-camera tools because the televiewer can be operated in boreholes with opaque fluids, although certain types of drilling mud in the borehole can affect the log. Successful operation of the tool is dependent on tool centralization, appropriate logging speed and formation/borehole conditions. Tool centralization is required to maintain equal distance travel time for the signals to reach the borehole wall. Because the tool samples 256 travel times and reflection amplitudes per rotation, a logging speed between 2 and 5 ft/min is required to insure effective scanning of the borehole wall. Signal response is affected adversely in boreholes greater than 14 in. in diameter. Some problems may be encountered because of formation characteristics and density. In “softer” formations, the sonic signal may not be strong enough to be received by the acoustic sensor. The more dense formations reflect the acoustic signal, and the log is better imaged. Because a magnetic declination sensor is used in the tool, measurements near metal casing cannot be made. Possible inconsistencies in graphic representation of acoustic-televiewer log signals, such as a non-vertical borehole, are given in Cohen (1995).

Televiewer images can identify the type, apparent size, and orientation of secondary-permeability features intercepting the uncased part of a borehole below the water column. However, these features are not necessarily permeable, and the size, and to a lesser degree the orientation of the feature at the borehole, may not be representative of formation conditions. In addition, televiewer images may detect wash outs of comparatively soft rock (shale, bentonite beds) or impressions in the borehole wall caused by drilling that can be misidentified as fractures.

Spontaneous Potential

The spontaneous potential (SP) log is one of a group of log types categorized as electric logs because they are based on the flow of electric current (fig. 40). The log measures the natural difference in electrical potential between an electrode in the borehole and a reference electrode at land surface. SP logging only can be done in the uncased portion of water- or mud-filled boreholes.

Small spontaneous differences in electrical potential are created by differences in salinity or pressure within the borehole and between the borehole fluid and the formation water (Rider, 1986). The major source of SP is the difference is electrochemical potential produced by differential rates of movement of dissolved ions through shale or through the mixing of water with differing salinity. Changes of SP voltages requires the presence of water with differing chemical properties in the aquifer, a means of segregating these waters within the aquifer, and a point where the waters mix. A lesser source of SP is the physical movement of water, which can generate “streaming potentials” because of differences in the flow of ions through the rock and chemical reactions in the vicinity of the borehole. Changes of SP voltages usually are strongest between contacts of differing lithology, particularly argillaceous and non-argillaceous deposits, or between waters of differing salinity. Changes in SP voltage can be associated with depths where water chemistry in either the borehole or the formation has changed, which can be caused by (among other things) inflow of water into the borehole. Therefore, SP logs can be used to identify secondary-permeability features as well as permeable features in a borehole. Similar to most electric logs, SP logs are affected by the presence of vertical flow of water within a borehole, which can obscure or eliminate differences in the electrical potential between the water in the borehole and the formation. These differences complicate log interpretation.

Single-Point Resistance and Normal Resistivity

Single-point resistance (SPR) logs measure the resistance (opposition of the material to the passage of an electrical current) between an electrode in the tool moving up the borehole and an electrical ground at land surface (figs. 40, A3). The current is induced by a generator and is emitted from an electrode on the SPR tool into the formation. The electrode also measures the resistivity of the formation to the current. Because the electrode spacing is small, thin beds and laminations can be sharply delineated, but investigation depth of the SPR log has no inherent lower resolution limit.

Normal resistivity logs measure millivolt response, calibrated to apparent resistivity (electrical resistance times unit length per unit area) of the formation to an electric current between an electrode on the tool moving up the borehole and an electrical ground at land surface, whereas resistivity is measured between another electrode on the tool and a reference electrode at the land surface. The spacing between the current emitting and potential-measuring electrodes on the tool typically is set at 16 in. (short normal) or 64 in. (long normal), which corresponds to about half the theoretical distance of signal penetration of each log. Although the depth of investigation increases with electrode spacing, the resolution decreases so that the signal associated with a feature (such as a fracture) with a thickness less than the electrode spacing may not be readily identifiable.

Generally, resistance decreases with increasing porosity, borehole diameter, fracture density, and dissolved solids concentration in the water. SPR and normal resistivity logging can provide information on changes in lithology and water quality that can be indicative of the presence of secondary-permeability features. However, these logs only can be done in the uncased portion of water or mud-filled boreholes. As with the other electric logs, the effectiveness of these logs is affected by vertical flow within a borehole obscuring differences in the electrical resistivity and conductivity of the water.

Neutron

The neutron log is one of a group of logs categorized as nuclear logs. A radioactive source in the tool emits neutrons into the formation. These neutrons then interact with hydrogen in the formation and sensors in the tool record the energy degradation of the neutrons as they pass through the formation and back to the sensor. The larger the amount of hydrogen encountered, the larger the amount of neutron adsorption from source to receptor, and the smaller the number of neutrons detected by the sensor (figs. 35, 40, A3). The log is, therefore, principally a measure of the hydrogen content of the formation, which typically is a function of its water content. Water can be present in pore space, or bound in the structure of formation minerals (Rider, 1986).

During ground-water investigations, neutron logs typically are used for estimation of porosity (figs. 35, A3). Although it is possible to calibrate the response of the neutron log to absolute values of porosity, neutron logs typically provide estimates of apparent porosity and typically are used only to evaluate porosity trends with depth.

Depth of investigation into an aquifer is dependent on the porosity but can range from about 2 ft with 0-percent porosity to 0.5 ft with 30-percent porosity (Serra, 1979). Generally, the neutron tool penetrates approximately 6-12 in. into the aquifer (Keys, 1990). The tool can be used in uncased or cased wells, in or out of water; however, the response of the neutron log is affected by whether the tool is in or out of the water column, differences in well diameter, and well construction. The use of a nuclear source for this log can pose regulatory difficulties related to transport and potential loss of the tool in a borehole. Calibration and interpretations of the response of the neutron logs to porosity frequently is complicated by the presence of clay minerals, which contain water molecules in their mineral structure, and shale deposits. These deposits have high total porosity but low effective porosity. Neutron-log calibration assumes that neutron flux is inversely proportionate to the log of the total formation porosity. As a result, the log is less sensitive to porosity at higher values.

Density

Density logs usually are used in combination with neutron logs to determine porosity. Density logs emit gamma rays, which are attenuated by collisions with electrons in the surrounding rock before being detected by a sensor on the logging tool. The counts detected by the probe is affected by the electron density in the formation, and is assumed to be inversely proportionate to the logarithm of the bulk density of the rock. Density logs can be calibrated to absolute values of bulk density for homogenous geologic materials. If the bulk density of the rock minerals is known (a pure dolomite with no pore space has a bulk density of about 2.85 grams per cubic centimeter) and the density of water is assumed to be 1 gram per cubic centimeter, calibrated bulk-density logs can be used to estimate the porosity of the deposit (Schlumberger, 1989). However, calibration is subject to a number of simplifying assumptions and density logs usually are used only to determine vertical trends in porosity for hydrologic applications. Density logs can be run in open or cased holes above or below the water column. Density logs do not provide a direct indication of porosity and are affected by the presence of shale that can be variably compacted.

Borehole Ground-Penetrating Radar

The borehole ground-penetrating radar (BGPR) tool can detect secondary permeability features, including fractures, at distances from 10 to 100 ft away from the borehole. Radar measurements can be made in a single borehole reflection (transmitter and receiver in the 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 and other secondary-permeability features. Cross-hole tomography can be used to estimate the orientation, location, and extent of these features between the boreholes. The movement of a saline tracer through permeable features can be monitored by BGPR.

BGPR uses the reflection and transmission of radar-frequency electromagnetic waves to detect variation in subsurface properties. The principles of borehole-radar reflection logging are similar to those of surface-radar profiling, except that antennas are connected together and lowered down the borehole. A radar pulse is transmitted into the bedrock surrounding the wellbore and moves into the formation until it encounters material with different electromagnetic properties, such as a fracture, void, or different lithology (fig. A4). At this location, some of the energy of the pulse is reflected back to the receiver, whereas the rest continues to penetrate the rock. A radar reflection profile along the wellbore is created by taking a radar scan as the antennas are moved up or down the wellbore. Different features produce a different reflection on the logs.

Cross-hole tomography is the process by which a two-dimensional model of physical properties in the plane between two wells is made. For these tomographic surveys, the transmitter antenna is placed in one well and the receiver antenna in the other. Numerous radar scans are made for each position by moving the receiver along the well at regular intervals. For each scan, the travel time and amplitude of the radar pulse is measured as it travels between the transmitter and receiver. These data then are used to create tomograms that map the radar-propagation velocity and attenuation properties of the rock between the boreholes (figs. A5, A6). Variations in velocity and attenuation can be interpreted to identify fractures, vugs, solution openings, differences in fluid properties, and lithologic contacts in the image plane.

Subsurface conditions and the available equipment limit the use of BGPR methods. In electrically conductive rocks, such as shale, or in saline water, radar waves may penetrate only 3-5 ft (Singha and others, 2000). In electrically resistive rock, the waves may penetrate 100 ft or more. Radar antennae capable of reading higher frequencies provide a more detailed image than those with lower frequencies, but are capable of a smaller distance of penetration. BGPR logs can provide data above and below the water table, but cannot penetrate through metal casing.

Temperature

Temperature logs record water temperature in the borehole (fig. 40). Abrupt temperature changes or subtle changes in the temperature gradient can be associated with inflow of water to the borehole through permeable features. Temperature is a common, easily performed geophysical measurement and can be used to identify permeable features under ambient conditions in the borehole being logged. Temperature logs also can be run in conjunction with pumping in another borehole to identify flow pathways between the pumped and logged boreholes (Robinson and others, 1993). Temperature logs must be run below the water level in an open borehole. Temperature gradients tend to be largest in the upper 5-10 ft of the water column because of interaction with the atmosphere, complicating identification of permeable features near the top of the water column. Changes in temperature and temperature gradients below the upper part of the water column usually are small and hard to identify, as are the precise depths of change.

Fluid Conductivity and Fluid Resistivity

The fluid-conductivity/resistivity log records both the electrical conductivity and resistivity of water in the borehole (fig. 40). Changes in fluid conductivity and resistivity reflect differences in concentration of dissolved solids in the borehole water. Changes in the conductivity or resistivity in the borehole water may be associated with inflow of formation water with different chemical properties and can be used to identify the location of permeable features. Fluid conductivity and resistivity logs must be run below the water column in an uncased borehole. The utility of these logs for identification of permeable features is affected by vertical flow in the borehole and requires water of differing chemical properties. The precise depth of the features also can be difficult to identify.

Borehole Dilution

Borehole dilution or hydrophysical logging is based on profiling changes in the fluid conductivity within a well or borehole through time after the water has been replaced or diluted with deionized water (Tsang and others, 1990; Pedlar and others, 1992). Measurements usually are performed in conjunction with pumping from the top of the water column to induce flow. Measurement of the changes in conductivity with depth through

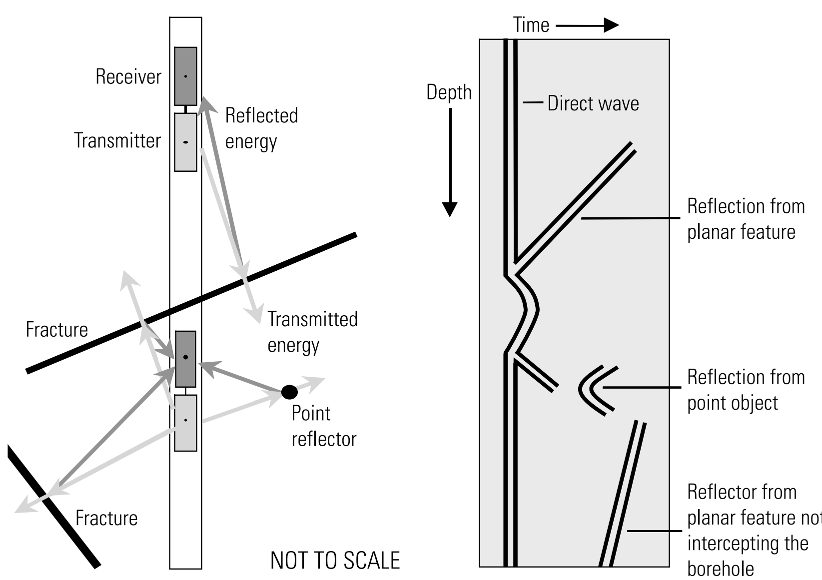


Figure A4. Orientation of borehole ground-penetrating radar transmitter and receiver in a single borehole and the resultant radar record from a fracture and a point reflector.

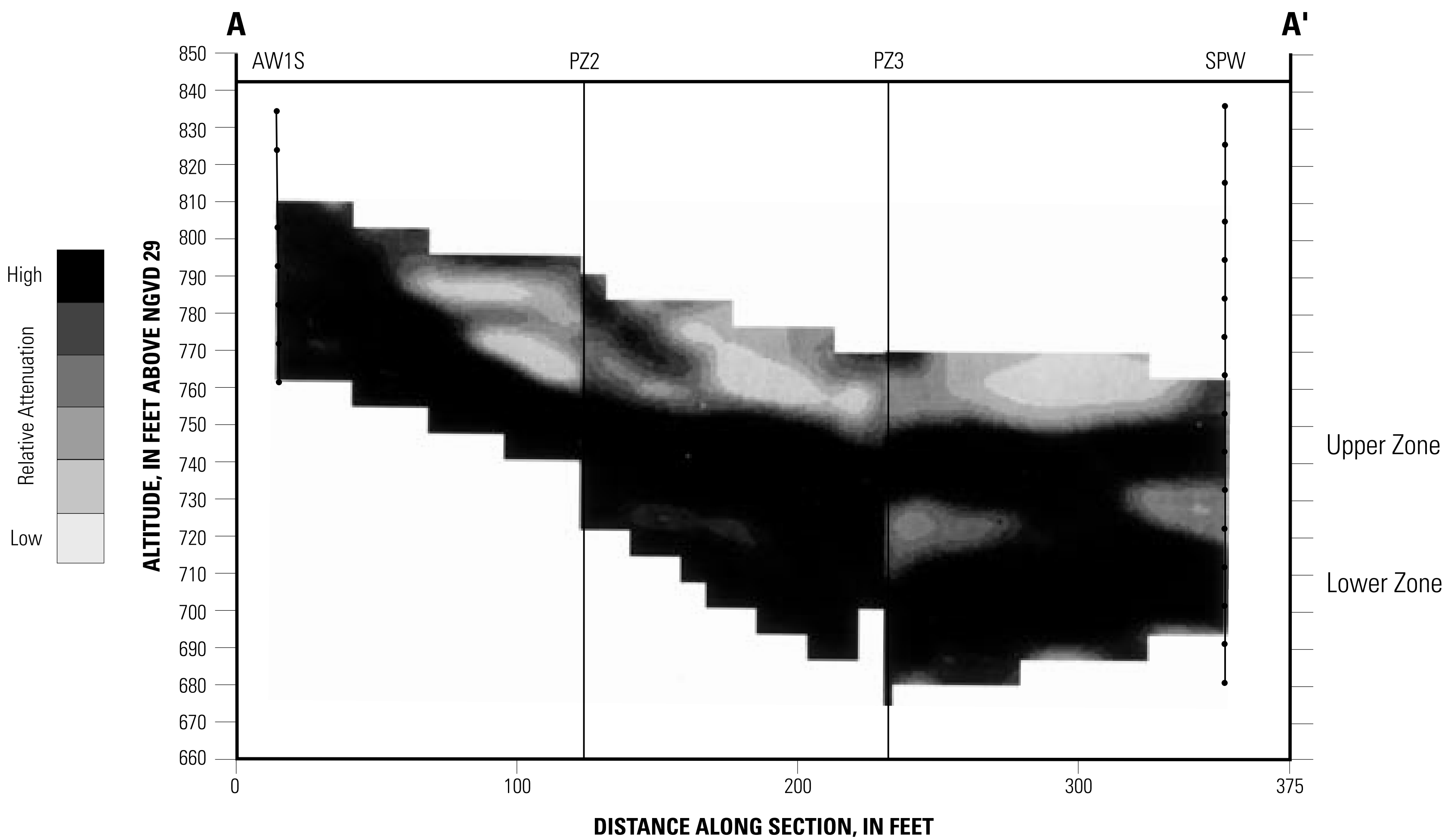


Figure A5. Attenuation tomogram between boreholes AW1S-PZ2, PZ2-PZ3, and PZ3-SPW, Byron site, Ill.

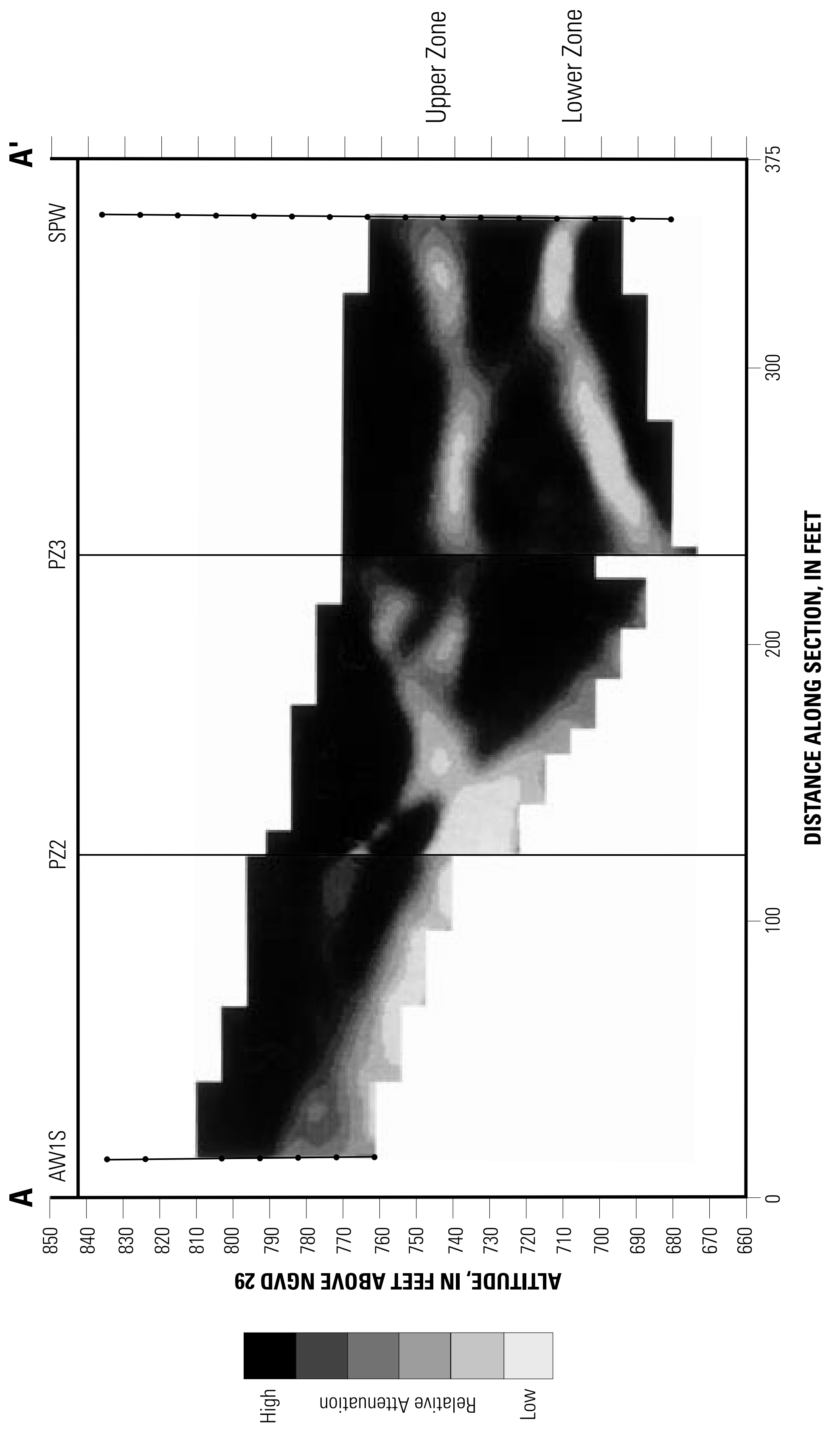


Figure A6. Velocity tomogram between boreholes AW1S-PZ2, PZ2-PZ3, and PZ3-SPW, Byron site, Ill.

time allow identification of the location of permeable intervals, the vertical direction of flow, and the rate of flow for each permeable interval. If reliable estimates of effective well radius can be obtained, hydrophysical logging results can be used to provide estimates of the transmissivity of each of the permeable intervals identified. In addition, hydrophysical logging can be used to interpret the fluid electrical conductivity of the formation water associated with each permeable interval and can be used in combination with other sampling devices to collect water-quality data from the formation at discrete intervals.

Hydrophysical logging can be used in detecting permeable intervals in both low- and high-permeability deposits that intercept the borehole and may have the capacity of detecting smaller amounts of flow (and less permeable features) than heat-pulse and impeller flowmeters can detect (Vernon and others, 1993). Hydrophysical logging can be performed below the water levels in an open borehole or the screened portion of a well. However, the need for deionized water for the logging increases the amount of time and effort required for this method.

Flowmeter

There are a number of different types of flowmeters, including heat pulse, impeller, and electromagnetic induction, each of which operate by different principals, all of which measure the velocity and direction (up or down) of vertical flow at various depths in a borehole. In a borehole of known diameter, water velocity can be converted to flow volume, which can be plotted to profile the vertical distribution of flow (fig. A3). Depth intervals where there are appreciable changes in the volume of flow between measurement stations are interpreted as intervals over which there is inflow to or outflow from the borehole (outflow being hereafter represented as negative inflow). These intervals frequently contain permeable vugs, fractures, or solution openings. In combination with acoustic televiewer logs, flowmeter logs can identify specific permeable features intersecting the borehole. Depending on the type of flowmeter being used and the configuration of the flowmeter measurement section, flowmeter logs can be used to measure discharge rates as low as 0.01 gal/min and as high as 100 gal/min. Flowmeter logs have a scale of investigation of about 10 borehole diameters, or about 5 ft for a 6-in. diameter borehole.

Open boreholes can create hydraulic connections between otherwise isolated fractures, solution openings and permeable beds, causing ambient hydraulic-head differences to drive flow along the borehole. Flow logging under ambient conditions can be an effective way to identify permeable zones in these boreholes. However, ambient flowmeter profiles can be ambiguous. For example, the absence of measurable vertical flow can be attributed to either the absence permeable features at the borehole or the absence of ambient hydraulic-head differences to drive the flow. In general, a single ambient flow profile is not sufficient to estimate the relative hydraulic conductivity of permeable intervals because the amount of inflow in any interval depends on the product of zone transmissivity and hydraulic-head difference driving the flow into the borehole. Furthermore, the water level in an open borehole tends to equilibrate near the hydraulic head of the most permeable feature intercepted by the borehole, minimizing the hydraulic-head difference between the water level in that feature and the water level in the borehole. Thus, natural hydraulic equilibrium can disguise the most transmissive features intersecting a borehole in any single flow profile.

The effects of hydraulic head can be separated from those of zone transmissivity in flowmeter log interpretation by obtaining flowmeter profiles under two hydraulic conditions (usually ambient and steady pumping or injection) (fig. A3). Molz and others (1989) and Paillet (1995) recommend subtracting the zone inflows measured under each of the two hydraulic conditions. This subtraction of inflows method effectively subtracts out the effects of background hydraulic-head variation, so that the differences (expressed as a percentage of the sum of all such differences) gives the relative transmissivity of each inflow zone. This relative transmissivity then can be converted to a quantitative estimate of zone transmissivity if another measurement is used to estimate total borehole transmissivity. Also note that it is assumed with this method that pumping or injection occurs at a rate small enough that “pipe” or friction flow losses associated with vertical flow in the actual borehole can be neglected in comparison with the hydraulic-head differences driving the flow.

A more quantitative approach to flow log interpretation is to simulate borehole flow using a borehole flow model (Paillet, 1998). This method requires that two parameters be estimated for each inflow zone (transmissivity and hydraulic head), and the model used to simulate the flow under ambient and stressed conditions (pumping or injection) and the measured drawdown (change in water level associated with the change from ambient to stressed conditions)(Paillet, 2000). The model parameters then are adjusted systematically until there is minimum difference between computed and measured borehole flow. The modeling method yields direct quantitative estimates of hydraulic head and transmissivity for each zone, but requires a definite estimate of the drawdown associated with the stressed part of the test. If cascading water during injection, lack of appreciable stress during pumping, or interference effects from other pumping in the area prevent accurate measurement of drawdown, the modeling method cannot be used. Although the model results appear to be equivalent to the results of slug testing of discrete intervals isolated by packers, measurement error associated with measurements made in the open borehole restricts the accuracy of model simulation. This result means that inflow associated with less permeable zones cannot be identified within the scatter in the flowmeter data. Paillet (1998) documents that zones with transmissivity two orders of magnitude less than that of the most transmissive zone in a borehole could not be detected in a comparison of flowmeter log interpretation with a set of straddle-packer hydraulic tests in the same boreholes.

Another application of flowmeter logging is cross-borehole testing. Cross-borehole flow logging involves flow logging in an observation borehole during pumping at a constant rate from an adjacent borehole. It is assumed with this method that inflow zones in observation and pumped boreholes already have been identified. Measurements are made in the borehole with the flowmeter held stationary, and the variation in flow with time (flow transient) is recorded as the pump is turned on and off. If there are N flow zones in the observation borehole, the flow transients are recorded at N-1 depth stations between the N zones, and at a depth station above all zones. Thus, there always will be as many data sets recorded as there are water-producing zones to quantify. Data analysis is performed by matching type curves computed with a borehole flow model with the measured transients. The shape of the type curve is used to indicate the nature of the fracture connections in the formation, and the matching of the type curves to the data yields estimates of transmissivity and storage coefficient for each zone (Paillet, 2001). The cross-borehole flowmeter logging is capable of identifying the presence of fractures not intersecting the borehole, and evaluates the properties of the flow path between the boreholes. Although this method is new and relatively few case histories provide independent verification of the method, one recent study indicates that the cross-borehole flow logging yielded results comparable to those obtained with straddle-packer hydraulic tests in the same formation (Williams and Paillet, 2002).

Flowmeter logging must be performed below the water level in an unscreened borehole. The efficacy of flowmeter logging is limited in low-permeability deposits and the representativeness of the flowmeter data are reduced by poor hydraulic connection between the borehole and the surrounding aquifer. Flowmeter logs are capable of detecting inflow though vugs, fracture, or solution openings where the permeability is within two orders of magnitude of the most permeable feature intercepted by the borehole (Paillet, 2001). As a consequence, less permeable features may not be detected in some boreholes. Flowmeter logging is not as widely available as many of the more conventional geophysical-logging methods. Flowmeter logging can be more time consuming and expensive to perform in comparison with other geophysical methods.

Water-Level Measurements

In addition to the hydrogeologic information provided with lithologic and geophysical logging, any assessment of hydrogeology and water quality requires, at a minimum, a thorough understanding of the direction of ground-water flow in three dimensions, as well as definition of the boundaries of the ground-water-flow system, including points of discharge to surface water. The water-level elevation measured in a properly constructed and located well represents the hydraulic head in the aquifer at the open interval of the well and is the principal source of information about the hydrologic stresses acting on an aquifer and how these stresses affect the ground-water system (Taylor and Alley, 2001). Because ground water flows from areas of high to low water-level elevation, plotting water-level elevations within the aquifer through space (the potentiometric surface) can be used to determine directions of ground-water flow and the boundaries of the flow system. In an aquifer with constant discharge through a uniform flow area, there is an inverse relation between hydraulic gradient and permeability of the aquifer. Therefore, variations in the horizontal or vertical-hydraulic gradients within an aquifer may indicate areas where there are variations in the horizontal or vertical-hydraulic conductivity of the aquifer. The scale of information provided by potentiometric-surface maps is dependent on the extent of the well coverage, but typically is on the order of tens to thousands of feet, resulting in the identification of large-scale features in the aquifer.

Limitations are inherent in the interpretation of potentiometric-surface maps. The first is that the development of a potentiometric-surface map usually assumes that the aquifer responds as a porous media, where flow can result in all directions, with the geologic materials affecting flow. In a flow system predominantly affected by a complex network of fractures, flow may not be fully represented with a potentiometric-surface map. Documented cases are present where flow may move in directions up to 180^{o} to what potentiometric-surface maps would indicate as the expected flow direction (Quinlan, 1989). A second limitation is that ground-water systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawal, and land use. As a result, ground-water levels vary through time and hydraulic conditions never are fully described. This variation makes the frequency of measurement one of the most important considerations in the design of water-level monitoring programs (Taylor and Alley, 2001). Infrequent water-level measurements at a subset of the total number of available wells at a site or at a single well may provide less insight into details of the site hydrogeology in comparison to more frequent measurements from a larger number of wells, but practical factors, such as budget constraints, may require fewer measurements. The necessary frequency of measurement should be considered in relation to the goals of the investigation as well as the presence of extraneous factors that can affect water levels, such as pumping from the aquifer or if measurements were taken during a period of abnormally low or high precipitation.

Single Measurement

A single measurement of many or all of the wells at a site can provide an accurate depiction of the water-level distribution if the measurements are taken over a sufficiently short time period (Taylor and Alley, 2001)(figs. 13, 19, 23, 24, 28). A single measurement of water levels allows the general direction of ground-water flow, the boundaries of the flow system, and potential variations in aquifer permeability to be identified for the measurement period. In combination with other data types, the water levels also can be used to estimate ground-water velocity. Single measurements are less expensive to collect than periodic measurements and may be adequate to assess hydraulic conditions if not collected during periods of abnormally high or low precipitation, if there is no substantial pumping from the aquifer, and if measurements were taken from an adequate number of properly located wells. However, a single measurement reveals nothing about seasonal or longer-term changes in hydraulic conditions and may not be representative of the full range in flow directions or flow velocities in an aquifer.

Periodic Measurement

Periodic water-level monitoring requires measurement of many or all wells at a site at some time interval, usually quarterly. Periodic measurement of water levels allows for variation or stability in the general direction of ground-water flow to be identified (figs. 23 and 24), can allow identification of the factors that affect variations in flow direction, allows for a realistic range of ground-water velocities to be calculated, can be used to help identify vertical and horizontal variations in aquifer permeability, and can provide a more accurate assessment of the variability of aquifer saturated thickness, which can affect flow and permeability. Periodic measurements are more expensive than single measurements but periodic measurements may be necessary to assess site conditions if flow directions vary because of pumping or seasonal variations in recharge from precipitation.

Continuous Measurement

Continuous water-level monitoring requires the installation of automatic water-level sensing and recording instruments that are programmed to make ground-water measurements at a specified frequency, usually at least daily. Continuous water-level measurements typically are obtained to determine the effects of variations in barometric pressure (fig. A7), nearby pumping, or recharge from precipitation on water levels.

Changes in barometric pressure can affect water levels in wells, the magnitude of water-level change being directly related to the barometric efficiency of the well (fig. A7). Barometric efficiency typically is high in confined aquifers (Todd, 1963; McWhorter and Sunada, 1977) and low in unconfined aquifers. Determination of the barometric efficiency of numerous wells in different parts of an aquifer has allowed previous investigators to identify the presence and location of confined and unconfined parts of an aquifer (Rasmussen and Crawford, 1996).

Offsite pumping may affect flow directions in an aquifer over a period of minutes to years, depending on the hydrogeology of the site and pumping rates. Variations in the water level in a well over a period of minutes or hours, because of offsite pumping, can be used to identify the presence and magnitude of changes in flow direction within an aquifer, as well as provide insight into flow pathways in the aquifer.

The distribution of recharge to a fractured-rock aquifer is affected by the degree to which the fracture network is connected to the ground surface. Water levels in wells that respond quickly to precipitation events are likely to be located in permeable parts of the aquifer, whereas wells that show little response to precipitation events may be located in less permeable parts of the aquifer.

Aquifer Tests

In addition to the hydraulic characterization that can be provided by water-level measurements, more detailed and more quantitative assessment of the aquifer and the secondary-permeability network can be provided by use of aquifer tests. Aquifer tests typically involve stressing the aquifer then monitoring water levels or water quality to enable identification of flow pathways and quantification of the physical properties that affect ground-water flow through specific secondary-permeability features as well as the aquifer as a whole.

Slug Tests

Slug tests involve instantaneous displacement of a volume of water from a well then monitoring water-level response through time as the water level returns to its equilibrium level. These data are analyzed to provide an estimate of horizontal hydraulic conductivity or transmissivity of the aquifer in the vicinity of the borehole. Methods used for data analysis depend on the aquifer type (confined or unconfined) and the manner in which the aquifer responds to the displacement of water.

Horizontal-hydraulic-conductivity estimates can be combined with porosity and water-level information to estimate ground-water velocity. Providing that a sufficient number of locations are available for testing, slug tests can be used to identify vertical and horizontal trends in aquifer permeability.

Slug tests are easy, quick, and inexpensive to perform once a well or borehole has been installed and developed. Estimates of hydraulic properties in deposits of all variations in permeability can be determined with slug tests. Data analysis requires hydrostatic conditions in the aquifer at the start of the test. Waiting for hydrostatic conditions to stabilize can be time consuming and expensive in a low-permeability deposit isolated by use of a packer assembly. Results of slug testing from water-table wells can vary over time because of changes in the saturated/unsaturated state of permeable features at the well. Slug tests also only monitor a small part of the aquifer, typically within 10 ft of the borehole. Analysis of slug-test data requires knowledge of well construction and aquifer geometry, including the length of aquifer open to the well, which typically is assumed to equal the saturated thickness of the well screen or the sand pack. Calculation of horizontal hydraulic conductivity typically assumes uniform flow into the aquifer along the entire saturated open interval of the well. In reality, most flow into the well in a fractured-rock aquifer will be through permeable fractures and solution openings, which usually have a thickness that is orders of magnitude less than that of the well screen. As a result,

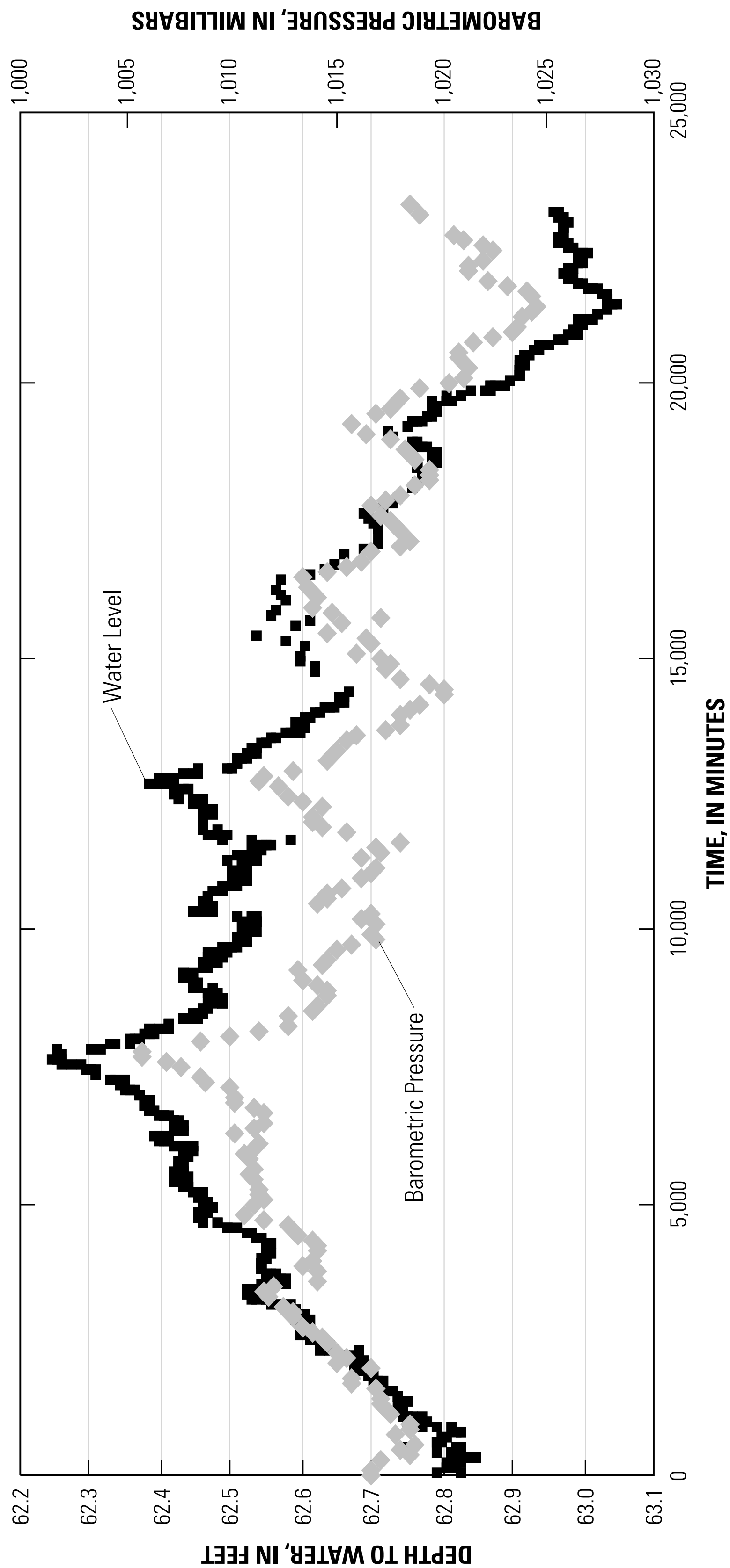


Figure A7. Water levels and barometric pressure in well AW5I, Byron site, Ill., June 30-July 16, 1993.

the calculated horizontal hydraulic conductivity (and dependent ground-water velocity) values appear to be orders of magnitude too low to represent the aquifer.

Conventional analysis of slug test data is based on an assumption that the tested interval can be conceptualized as a porous media. In cases where slug tests are used to evaluate isolated intervals containing fractures, this conceptualization holds most appropriately where the density of conductive fractures is high and where there either is virtually no fluid exchange between fractures and matrix or the rate of exchange is extremely rapid (Butler, 1998). If these conditions are not met, other aquifer conceptualizations must be used. The discrete fracture model (Wang and others, 1977; Karasaki and others, 1988), or the double-porosity model (Moench, 1984) usually are utilized in the alternate conceptualization.

Specific-Capacity Tests

Specific-capacity aquifer tests involve extraction of water from a well at a known, constant rate (Q) and taking a single measurement of the amount of water-level decline in that well (s) at some known time (t) after the initiation of pumping. The specific capacity (Q/s) is the ratio of the discharge rate to the total decline in water level in the well. Specific capacity is a measure of the productivity of the well and the aquifer. The higher the specific capacity, the more productive the well and the aquifer.

Specific-capacity data can be manipulated to provide an estimate of transmissivity (T), and by extension horizontal hydraulic conductivity, of the aquifer in the vicinity of the borehole using the Theis equation (Todd, 1963), where

$$T = [Q/(s)][2.3/4\pi][\log(2.25Tt)/(r_e^2S)]. \qquad (1)$$

Because the T term appears twice in this equation, solution for T involves an initial estimation for the value of T, then iterative solving of equation (1) for Q/s using refined estimates of T until the observed value of Q/s is approximated.

If the value for the storage coefficient (S) of the aquifer is unknown (as frequently is the case), both T and S are estimated for solution of equation (1). The effective radius of the well (r_e) typically is assumed to be equal to the nominal radius of the well (r_w). However, r_e can be substantially larger than r_w, particularly in fractured-rock aquifers (Mace, 1997). Specific-capacity analyses typically assume that well loss is negligible. Calculated transmissivity values are moderately insensitive to large changes in the assumed values of r_e and S. However, uncertainty regarding the true values for S and r_e, and assumptions regarding the absence of well loss and the presence of a fully penetrating well in a confined, homogenous, isotropic aquifer results in T estimates from specific-capacity tests that usually are substantially greater than estimates obtained with other methods (Huntley and others, 1992).

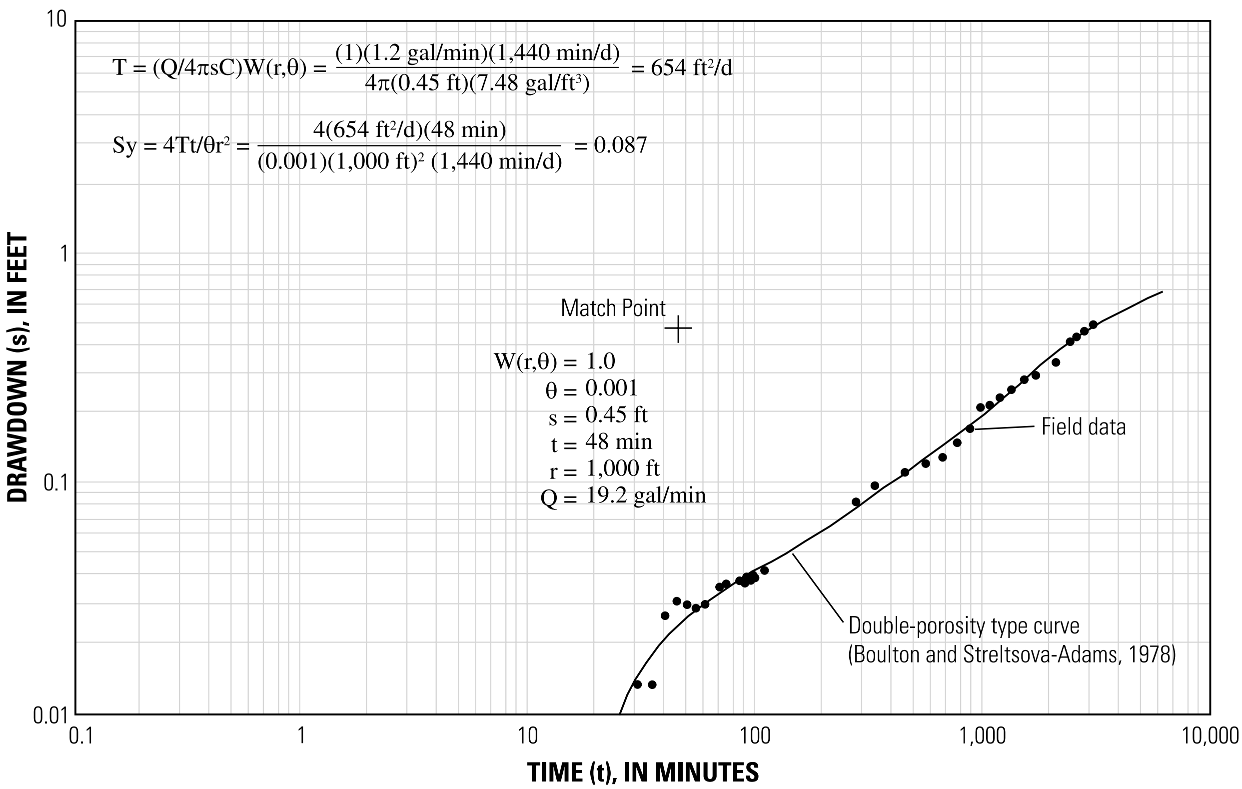
If a sufficient number of specific-capacity tests are available, these data can be used to identify spatial variations in the hydraulic properties of the aquifer. Specific-capacity tests cannot be used to identify vertical variations in aquifer properties without additional information. Specific-capacity data frequently are reported on well logs for water-supply wells on file with various agencies and can be used to obtain preliminary estimates of aquifer transmissivity. Specific-capacity tests typically are easy, quick, and inexpensive to perform if pumping already is being done for well development and the test can be performed in conjunction with or immediately after development. Specific-capacity tests as a stand-alone procedure typically are moderately easy, quick, and expensive to perform. These tests can be difficult and expensive to perform if treatment of the discharge water is required. Although specific-capacity tests theoretically can be performed at any realistic permeability range, as a practical matter the requirement for sustainable drawdown limits the effectiveness of this method when applied to deposits of low and high permeability. Specific capacity in wells cased above the water table can vary over time because of changes in the saturated/unsaturated state of permeable features in the upper part of a well. Additionally, dewatering productive intervals during pumping can result in increased drawdown in the well and an underestimation of aquifer transmissivity. The extent of the aquifer stressed by a specific-capacity test depends on the aquifer properties, the pumping rate, and the pumping duration; these tests typically stress the aquifer between about 100 and 1,000 ft from the pumped well.

Multiple Well Tests

Multiple-well, constant-discharge tests involve extraction of water from a well at a known, constant, rate while monitoring the amount of drawdown through time in the pumped and observation wells (wells where drawdown is measured). Plots of drawdown with time in the observation wells on a log-log scale can be compared with type curves of the theoretical aquifer response to quantify the transmissivity, storage coefficient, and horizontal hydraulic conductivity of the aquifer (Todd, 1963)(fig. A8). Analysis of the spatial distribution of drawdown at a given time during the test can be used to identify the presence and orientation of horizontal and vertical flow anisotropy in the aquifer caused by the orientation and distribution of secondary-permeability features in the aquifer.

The amount of the aquifer stressed with a multiple-well aquifer test depends on the hydraulic properties of the aquifer, the pumping rate, and the duration of pumping, but these tests typically provide information on aquifer properties between 100 and 2,000 ft from the pumped well. Therefore, multiple well, constant-discharge aquifer tests allow the calculation of hydraulic properties over the largest area of the aquifer possible with current methods. These aquifer tests also provide the most comprehensive direct insight into the three-dimensional pathways of ground-water flow.

Multiple-well tests require extensive planning, typically are performed for at least 1,000 minutes, and large amounts of manpower and equipment are required. In addition to measurement of water levels and discharge, water-level data collected during long-term, multiple-well tests typically must be adjusted to correct for water-level fluctuations caused by ambient effects, such as changes in barometric pressure, pumping from offsite wells, and recharge to ground water. As a consequence, these tests are the most difficult, time-consuming, and expensive types of aquifer tests to perform and analyze. The degree of time and expense increase substantially if the extracted water requires treatment prior to disposal or additional wells need to be drilled to support the testing. The requirement for sustainable drawdown in the pumping well and transmission of drawdown from the pumping well to observation wells effectively precludes the use of this method in deposits of low permeability. The requirement for measurable drawdown in the observation wells and the expense associated with treatment and disposal of contaminated water also may limit the use of



ABBREVIATIONS

T = Transmissivity, in ft²/d (feet squared per day)
Q = Discharge, in gal/min (gallons per minute)
s = Drawdown, in ft (feet)
C = Conversion factor, converts gallons to ft³ (cubic feet)
W(r,θ) = Double porosity type curve well function
r = Radial distance from the pumped well, in ft (feet)
θ = A value defined as equal to (4Tt)/(Syr²)
Sy = Specific yield (dimensionless)
t = Time since the start of pumping, in minutes

Figure A8. Logarithmic plot of drawdown as a function of time for borehole PW-3 matched with theoretical double-porosity type curve, Byron site, Ill.

this method in high-permeability deposits. Aquifer-test results in water-table aquifers can vary with time because of changes in the saturated/unsaturated state of permeable features in the upper part of the aquifer. Additionally, dewatering productive intervals during pumping can result in a decrease in the amount of water discharged to the well from some parts of the aquifer with a concomitant increase in the discharge to the well from other parts of the aquifer. Depending on the configuration of the fracture network in the aquifer, these changes in discharge can affect the drawdown data and invalidate their use for calculation of aquifer hydraulic properties.

There are numerous methods for analysis of multiple-well, constant-discharge aquifer-test data. The most appropriate method depends on whether the aquifer is confined or unconfined, the degree to which the aquifer approximates an equivalent porous medium, whether the aquifer functions as a double-porosity media, and the presence of a preferred orientation of the vertical fractures in the aquifer. An overview of each of these methods is beyond the scope of this report. Although many methods can be applied in anisotropic aquifers, it is assumed in all methods that the aquifer is homogenous at the scale of the test.

In a homogenous, isotropic aquifer, drawdown occurs in a circular pattern centered on the pumped well, with the amount of drawdown being dependent on the distance from the pumped well and independent of direction. The presence of vertical fractures in many fractured-rock aquifers results in an anisotropic response to pumping with the amount of drawdown being dependent on both the orientation and distance from the pumped well (fig. A9). Pumping in an anisotropic aquifer produces an elliptical drawdown distribution where the direction of maximum drawdown typically is parallel to the primary orientation of the vertical fractures in the aquifer, with the direction of minimum drawdown oriented perpendicular to this direction. A minimum of three wells penetrating the entire thickness of the aquifer is required to identify the shape of the drawdown ellipse in two dimensions.

In addition to vertical anisotropy in the aquifer, horizontal variations in aquifer permeability and hydraulic interconnection also may produce variations in drawdown at a given location at different depths in the aquifer (fig. A9). Because variations in drawdown with depth in the aquifer cannot be identified in fully penetrating boreholes, important information regarding vertical and horizontal hydraulic interconnection within the aquifer as well as the hydraulic properties of specific secondary-permeability features may not be determined. Cross-hole testing, where packers are used to isolate specific intervals of both the pumped and observation boreholes, can be used to provide a more detailed aquifer assessment.

Tracer Tests

Tracer tests involve the injection of a compound (tracer) into the aquifer in sufficient amounts to raise the concentration of the tracer substantially above its ambient level and monitoring the tracer concentration with time in the aquifer downgradient of the point of injection. For most applications, the tracer is a non-reactive dye or ion, such as chloride or bromide, and it is assumed that the rate of tracer migration is identical to the rate of ground-water flow. There are two basic types of tracer tests; natural gradient (tracer moves in response to natural hydraulic conditions) and induced gradient (tracer moves in response to hydraulic conditions induced by pumping or injection). Only induced-gradient tracer tests are discussed here.

Induced-gradient tracer tests require pumping at a known, constant rate from an extraction well and injection of the tracer in an observation well. Analysis of tracer-test data requires measurement of the distance between the extraction and injection wells, and measurement of the water-level altitude in the extraction and injection wells (converted from measured time-drawdown data) during the test period. Analysis of tracer-test data requires that the flow regime in the aquifer be approximately stable prior to and after tracer injection. A stable flow regime requires an absence of pumping or recovery from offsite wells, approximately steady-state conditions prior to and after tracer injection, tracer injection at a rate slow enough to induce minimal water-level increase at the injection well, and tracer concentrations low enough so that density-driven flow is not induced.

A short-term injection tracer test involves addition of a slug of tracer over a small time period (minutes) at the injection well then plotting tracer concentration with time in the water from the extraction well (fig. A10). Depending on the goals of the investigation, tracer testing in fully penetrating boreholes can be performed to assess the hydraulic properties of the bulk aquifer, or tracer testing can be done in discrete intervals to assess the hydraulic properties of specific features. The time required for the peak concentration of tracer to move through the measured length of aquifer under the measured horizontal hydraulic gradient (dh/dl) provides a direct measurement of the velocity of the water through the aquifer under the conditions induced by the pumping and injection. Determination of ground-water velocity (v) permits solution of the Darcy equation

$$v = (Kh/n_e)(dh/dl), \qquad (2)$$

for either Kh or n_e (effective porosity), depending on which parameter already is known. Typically, Kh can be determined readily from analysis of the time-drawdown data collected during the tracer tests or from aquifer tests done in different parts of the aquifer, so tracer tests are typically used to estimate n_e.

Assessment of the tracer concentration in the extracted water through time can provide insight into the degree of hydraulic interconnection and tortuosity of the secondary permeability network (dispersion), as well as the degree of hydraulic interaction between the secondary and primary porosity in the aquifer (diffusion). In an aquifer dominated by secondary permeability, dispersion largely results from variations in the fluid velocity

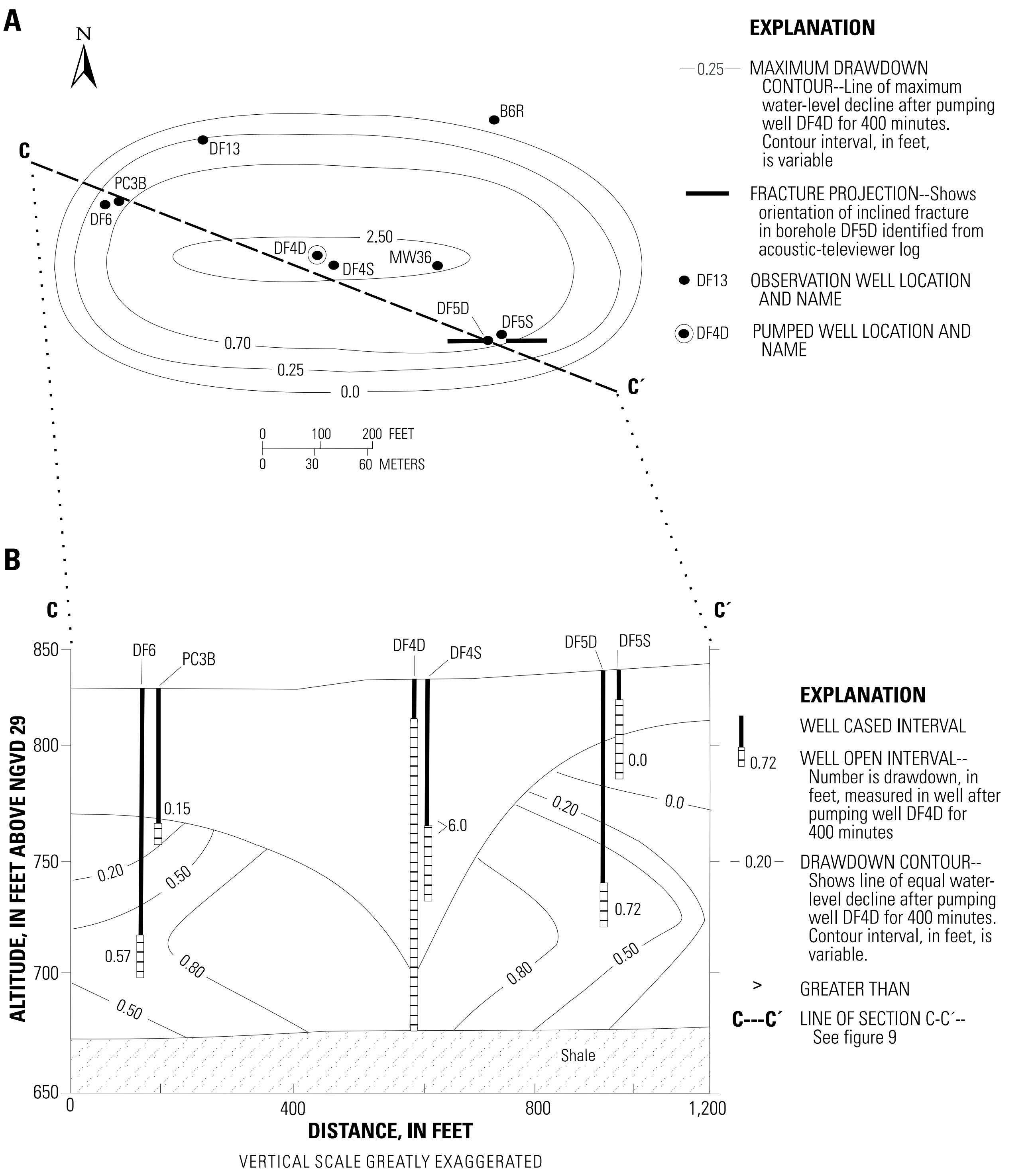


Figure A9. Distribution of drawdown in the Galena-Platteville aquifer after pumping borehole DF4D for 400 minutes, Byron site, Ill., February 2, 1992, A) maximum drawdown in the aquifer; B) drawdown in the aquifer along line of section C-C´.

within a fracture or solution opening and differences in water velocity through different fractures or solution openings. Tracer concentrations that increase rapidly above background concentrations to a maximum value, then decrease rapidly to background concentrations, indicate a low dispersion coefficient and flow through a single fracture or solution opening, or a simple network of fractures or solution openings, with uniform hydraulic properties. Tracer concentrations that increase slowly to a maximum value, then decrease slowly to background concentrations, indicate a comparatively large dispersion coefficient and flow through a complicated network of fractures or solution openings, with variable hydraulic properties.

An accurate value for dispersion and diffusion coefficients is important for a thorough characterization of ground-water flow and contaminant transport, and these coefficients only can be calculated from tracer-test data. For this reason, tracer tests are a useful method for the characterization of fractured-rock aquifers. Short-term injection tracer tests typically are expensive to perform and require extensive understanding of the secondary-permeability network and the flow pathways between the injection and extraction wells to maximize the amount of information that can be obtained from the test. Tracer tests performed in conjunction with pumping usually provide information on the hydraulic properties of the aquifer over a length of tens to hundreds of feet. Because the coefficient of dispersion tends to increase with an increase in the length (scale) of the aquifer being studied (Xu and Eckstein, 1995), the representativeness of any given dispersion coefficient is uncertain.

A continuous injection tracer test involves continuous injection of tracer at a constant concentration during a substantial portion (hours or days) of the test. As is the case for a short-term injection tracer test, the time required for the tracer to move through the measured length of aquifer under the measured horizontal-hydraulic gradient provides a direct measurement of ground-water velocity through the aquifer, which allows equation 2 to be solved for n_e. Because continuous injection of tracer does not allow for analysis of variation in tracer concentration through time as the tracer slug migrates through the aquifer, continuous-injection tests cannot be used to estimate coefficients of dispersion and diffusion and have little value for quantifying the hydraulic properties of an aquifer. However, continuous injection of a chloride tracer of sufficient concentration will result in the flow pathways between the injection and extraction wells being filled with tracer water substantially more conductive than that of the ambient water. Cross-borehole radar tomography can be run in boreholes straddling that part of the aquifer through which the tracer is to move before and during injection. Comparison of the tomograms before and during injection will identify the location of the highly conductive water in the aquifer, thereby identifying the flow pathways and secondary-permeability features in the aquifer (fig. A11). Cross-borehole radar tomography run while the tracer is migrating from the injection well to the extraction

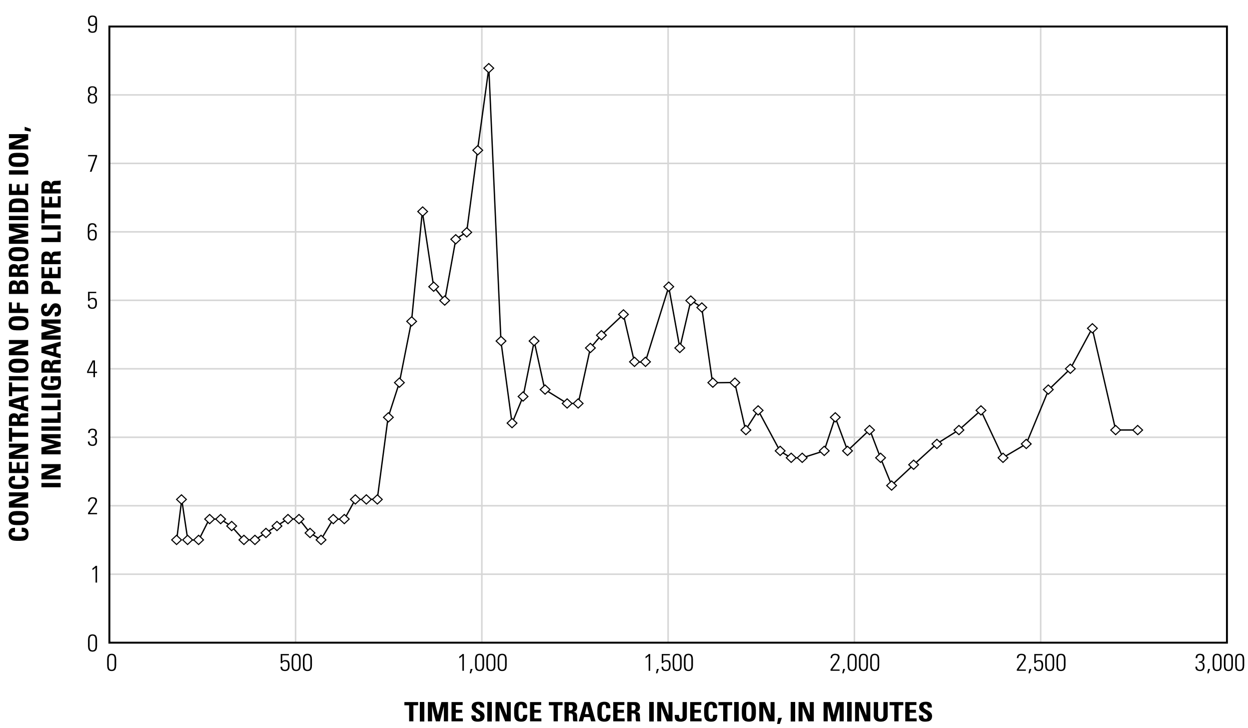


Figure A10. Concentration of bromide ion tracer in water pumped from borehole SPW, Byron site, Ill., July 12-14, 1992.

well also can be used to determine the approximate rate of flow through the aquifer in response to the hydraulic conditions induced by pumping and injection.

Continuous injection tracer tests performed in conjunction with cross-borehole radar tomography, along with multiple-well, constant-discharge aquifer tests and flowmeter logging performed in conjunction with pumping from nearby wells, are capable of providing a comprehensive assessment of the specific pathways for ground-water flow in fractured-rock aquifers. Borehole tomography also allows assessment of specific flow pathways within the aquifer without the need to isolate discrete intervals of the aquifer. In addition to the extraction and injection wells, and the equipment needed to for the tracer tests, long-term injection tracer tests performed in conjunction with cross-borehole radar tomography may require installation of boreholes to allow access to the aquifer, may require extensive aquifer characterization prior to beginning the testing, and may require intensive personnel commitments. Additionally, borehole ground-penetrating radar equipment and personnel experienced in analysis of these data are not readily available and the need to induce an appreciable contrast between the pre- and post-tracer conductivity of the water can result in ambiguous identification of some flow pathways. Long-term injection tracer tests performed in conjunction with cross-borehole tomography are expensive to perform. These tracer tests usually provide allow aquifer characterization over a length of about 20 to 300 ft.

Water Chemistry

Assessment of an aquifer and its secondary-permeability network usually can be obtained by analysis of spatial or temporal patterns in the concentration of a given chemical, or group of chemicals in the aquifer. Because dissolved chemicals are transported in the ground water, they can provide a more direct depiction of flow pathways than usually can be obtained using hydraulic and geophysical methods, which usually represent generalized flow directions.

The location and extent of natural and anthropogenic constituents dissolved in ground water can be used to identify the pathways of ground-water flow (fig. 15). This method of analysis differs from a tracer test in that the chemical constituent used to identify the flow pathway is present in the aquifer as the result of natural or anthropogenic processes, not introduced into the aquifer as part of an investigative method. Because the surficial location of the contaminant source material at most waste-disposal sites is well defined, and because many of the contaminants are not found in nature, identifying the distribution of one or more contaminants in the aquifer can be used to define the pathways of ground-water flow through the fractured rock. The distribution of contaminants in a fractured-rock aquifer can be used to identify specific pathways of ground-water flow, hydraulic interconnection within the aquifer, and hydraulic boundaries of the flow system. Analysis of contaminant distribution also can be used to determine if offsite pumping or temporal variations in precipitation substantially affects flow directions.

Implicit in the analysis of water chemistry is the assumption that contaminants are derived from known source areas and contaminant migration is solely in the dissolved phase. The presence of unidentified surface source areas or nonaqueous phase liquids in an aquifer may result in erroneous interpretations about flow in the aquifer. Because identification of the three-dimensional nature and extent of contamination usually is a requirement for investigation of any waste-disposal site, analysis of the distribution of contamination in an aquifer as a means of aquifer characterization can be considered as both inexpensive and expensive to perform. Analysis of the distribution of contamination in an aquifer allows characterization of the aquifer over the length and width of the plume, typically a distance of hundreds to thousands of feet.

Analyses of the spatial distribution of contaminants and other chemical constituents and indicators of water quality can be useful in identifying pathways of preferential flow within fractured-rock aquifers and the extent of hydraulic interconnection within and between secondary-permeability features in the aquifers. For example, delineation of the distribution of volatile organic compounds (VOC's) with depth in an uncased borehole may identify a substantial increase in VOC concentrations that is restricted to a specific depth. Similarly, delineation of the distribution of water temperature or dissolved oxygen concentration with depth may identify a change in one of these indicators of water quality. These depth-specific changes may represent locations of preferential flow pathways in the aquifer.

Analyses of major ions to determine water chemistry or concentration of selected constituents, such as tritium, may be used to determine to what extent an aquifer, or part of an aquifer, is confined. Differences in water chemistry among sample locations may indicate that a low permeability unit separates flow in different parts of the aquifer, thus, limited movement of contaminants between these locations is expected. Tritium is a radioisotope of hydrogen that can be used to estimate relative age of ground water and extent of confinement and vulnerability of aquifers to contamination. Beginning in 1954, with the onset of above-ground nuclear-weapons testing, naturally occurring levels of atmospheric tritium were increased from about 5 tritium units (Kauffman and Libbey, 1954)(TU's; equivalent to 16 pCi/L) to over 1,000 TU's. Tracking the pulse of tritium-enriched water recharging aquifers allows the time since initiation of recharge to be estimated. Presently (2002), ground water with levels at or less than 1 TU represents recharge that originated before about 1954. Water with tritium levels at or less than 1 TU are considered to be derived from a confined aquifer; thus, the aquifer is not vulnerable to contamination (Illinois Environmental Protection Agency, 1999). Water with tritium levels at or greater than natural levels of 5 TU's are considered to be derived from unconfined aquifers; thus, vulnerable to contamination.

Numerical Modeling

Computer numerical modeling of fractured-rock aquifers can be useful to understanding flow and contaminant transport at various spatial scales. Because of the heterogeneity of fractured-rock aquifers, consideration of model selection in regards to scale and study objectives and evaluation of model uncertainty is important. Development of numerical models requires integration of data from various scientific disciplines, including geology, geophysics, hydrology, and hydrogeochemistry. At all scales of application, models should be considered simplified characterizations of

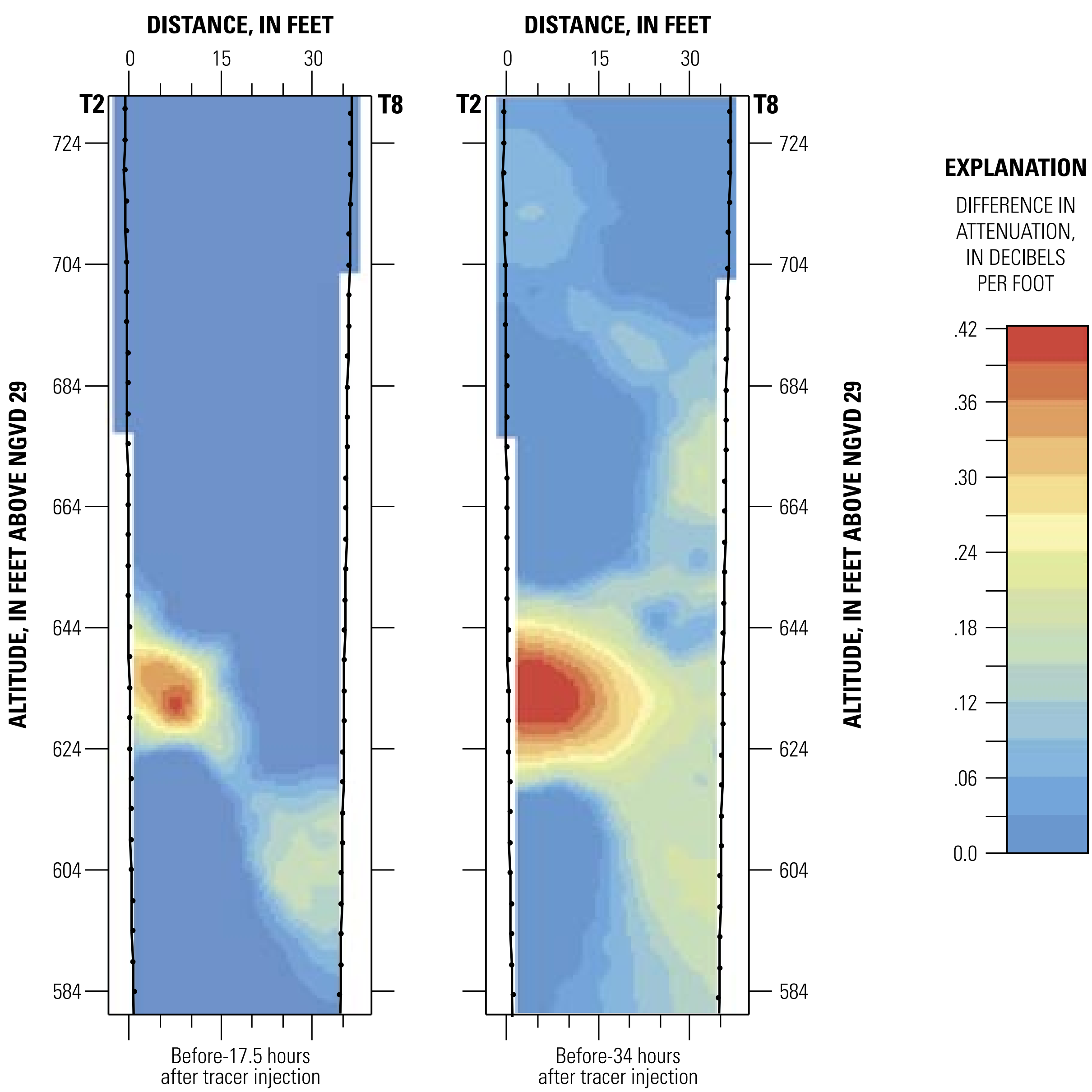


Figure A11. Borehole-radar difference tomogram showing changes in attenuation between boreholes T2 and T8, 17.5 and 34 hours after tracer injection in borehole T1, Belvidere, Ill.

complex ground-water systems. Development and limitations of numerical models, particularly as applied to fractured-rock aquifers, are discussed in detail by the National Research Council (1996).

For large-scale evaluations of aqueous flow, (regional to subregional) continuum-based (porous-media) models, such as MODLFLOW (McDonald and Harbaugh, 1988; Harbaugh and others, 2000) have been used successfully (Mercer and Faust, 1986). In such applications, the scale of investigation is considered large enough for the aquifer to be represented as an equivalent porous media. Post-processing routines, such as MODPATH (Pollock, 1989; 1994) using particle tracking, can aid visualization of the simulated flow patterns. However, because flow patterns are generalized over large areas and property values averaged over large areas usually are estimated on the basis of small-scale measurements, the spatial accuracy typically is unacceptable for subsequent simulation to detail the distribution, travel times, and concentrations of contaminants associated with preferential flow paths or over areas smaller than designated model-cell sizes (National Research Council, 1996). Research also indicates that application of porous-media models may not be appropriate at any scale of investigation, because fracture features that preferentially affect flow are present at all scales of interest (National Research Council, 1996).

Continuum-based models also have been applied to fractured-bedrock systems in which a proportion of flow is through the matrix (doubly-porous media). These dual-porosity models (Glover, 1987, for example) are treated as overlapping continuum models that generally are applied to smaller-than-regional scale settings (Mercer and Faust, 1986). For these models, the hydraulic properties of the matrix (low permeability and high porosity) and fractures (high permeability and low porosity) are considered; the geometry of the fracture network generally is represented in a simplified fashion. Whereas these models can approximate steady-state, matrix-to-fracture leakage, these models are considered most useful for assessing transient flow over periods of tens of years, thus, accounting for the differences in timing of hydraulic response in matrix and fractures. Three principal limitations to these models are (1) the geometry of fracture networks is oversimplified, (2) accurate representative estimates of the hydraulic properties are difficult to obtain, and (3) uncertainty in identifying the scale at which continuum assumptions are valid (National Research Council, 1996).

For small-scale (site to fracture scale) evaluations of aqueous flow, discrete-flow pathway models are best applied. Each fracture is considered discretely with these models. These models require that the heterogeneity of the geometry (aperture, orientation, length, connectivity, density) and hydraulic properties (hydraulic conductivity) of the fracture(s) be well characterized. Particularly difficult aspects of the data requirements for application of these models are field-determination of the geometry of the conductive parts of fracture networks and fracture transmissivity (National Research Council, 1996). Development of these models was limited until the late 1980's, when interest in characterizing and remediating contaminated fractured-rock aquifers expanded rapidly. Since that time, various deterministic (property values generally are known) and stochastic (property values randomly distributed and described by a probability distribution) models have been developed. Aquifers with a well-developed network of fractures may be best suited to stochastic modeling. The most favorable conditions for application of these models include: (1) statistically uniform fracture pattern, (2) obtainable statistically representative sample, (3) simple fracture distribution, and (4) statistically described fractures are fluid filled (National Research Council, 1996).

Discrete-flow pathway models are not readily available and have not been fully verified in the field. Additionally, resources generally are unavailable for the accurate characterization of complex fractured-bedrock systems that is necessary for preparation of accurate local-scale models. Presently (2004), these models are considered by many users to be research tools used for theoretical evaluation of fractured flow; most of their use has been limited to this application. The models have been used successfully in some field-scale studies over lengths less than about 300 ft (National Research Council, 1996). Future advances in aquifer characterization and model development are expected to result in improved accuracy and increased use of these models.

Hybrid models incorporate the approaches and capabilities of continuum and discrete-flow pathway models. Hybrid models are considered most useful in estimating large-scale continuum properties (which generally cannot be measured) based on field-scale, discrete-fracture determinations (National Research Council, 1996).

The complexities of simulating contaminant distribution in fractured-rock aquifers are greater than that of simulating ground-water flow in these aquifers. Pathways for contaminant movement must be delineated accurately and factors that affect advective flow (including effective porosity) and dispersion (mechanical mixing and molecular diffusion of contaminants) in fractures must be estimated accurately. Complex chemical or biochemical reactions, or radioactive decay that can result in changes in contaminant mass usually need to be considered. In these cases, fluid and rock chemistry need to be well determined. Data requirements are more substantial if dual-porosity conditions are present and contaminant movement between fractures and matrix must be simulated. A partial listing of presently developed models of aqueous and contaminant flow in fractured-rock aquifers is given by the National Research Council (1996).

Packer Tests

Characterization of fractured-rock aquifers through the use of open boreholes has a number of disadvantages related to the inability to measure the hydraulic and chemical properties of individual secondary-permeability features intercepted by the borehole. First, the precise location of the permeable features usually cannot be identified without a flowmeter survey or other type of investigation. Second, if multiple fractures are present, water quality and hydraulic response will be a composite of each permeable feature, possibly resulting in an inaccurate characterization. Third, wellbore-storage effects may dominate response if the matrix is of low permeability (National Research Council, 1996). Borehole packers are pneumatic or mechanical devices that isolate sections of a borehole by sealing against the borehole wall, leaving an isolated zone above or below a single packer, or between two packers separated by some distance (fig. A12). The use of packers to isolate specific parts of the borehole reduces or eliminates the effects of these shortcomings by allowing collection of hydraulic and water-quality data from discrete intervals over the entire length of the wellbore. Packers also prevent cross contamination resulting from vertical flow within the wellbore.

Water-quality sampling or hydraulic testing using a packer assembly typically is expensive and time consuming to perform. The large amount of time required for low-permeability intervals to reach hydrostatic conditions or recharge from pumping may serve as a practical barrier to packer testing in some boreholes. Vertical flow within a borehole also can transport contamination within the aquifer from zones of higher to lower head (Williams and Conger, 1990). This transport can produce sampling results indicating contaminant distribution within the aquifer that may not represent in-situ conditions. As a consequence, analysis of water-quality data from discrete intervals in open holes can be ambiguous or erroneous (Johnson and others, 2001). Installation of a packer system soon after drilling minimizes cross contamination and helps ensure collection of representative water-quality samples (Johnson and others, 2001).

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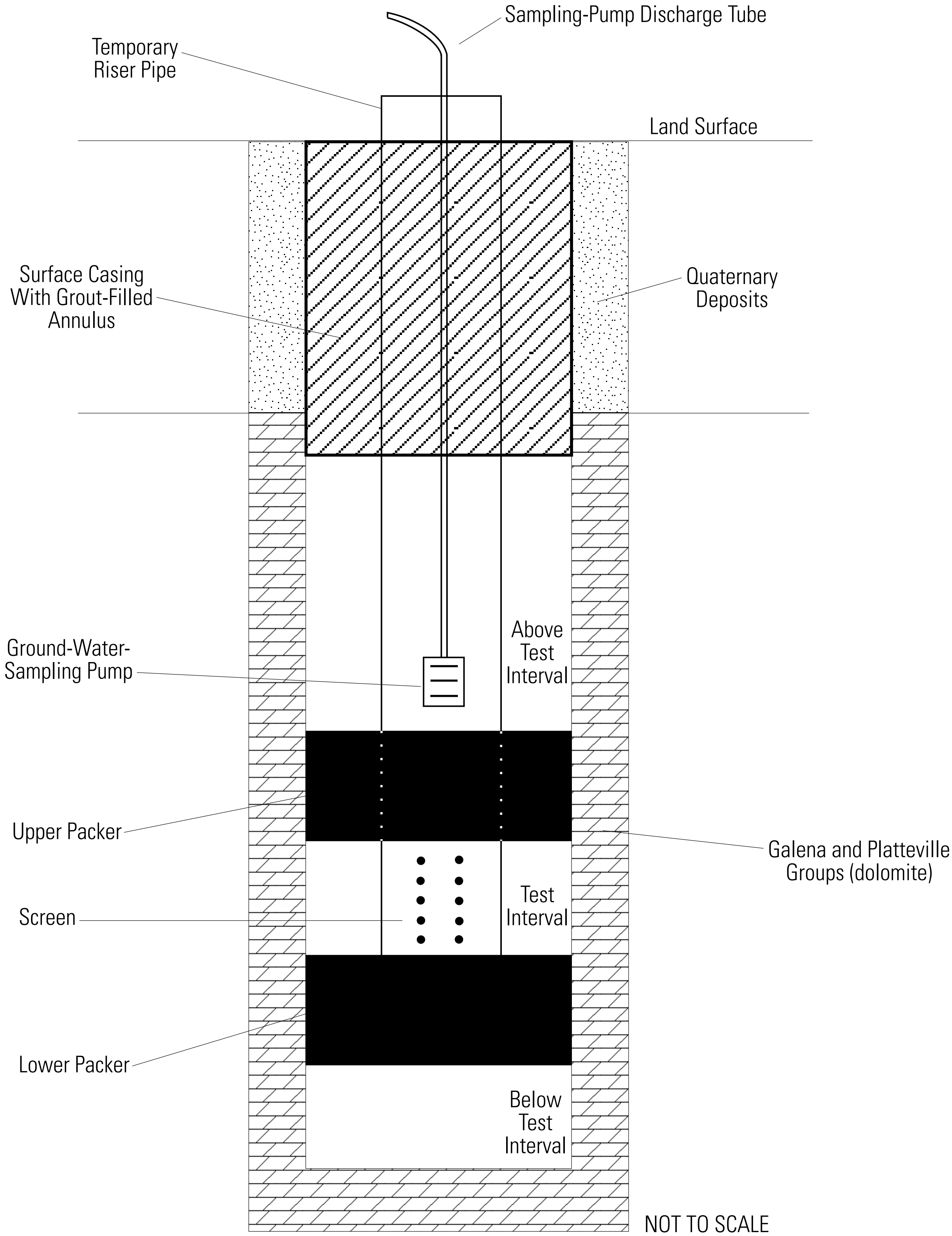

Figure A12. Packer assembly and ground-water sampling pump in a borehole.

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