Borehole Geophysical Applications in Karst Hydrogeology

Frederick L. Paillet
U.S. Geological Survey, PO Box 25046, MS 403, Denver, CO 80025

Abstract

Geophysical measurements in boreholes provide useful information about subsurface aquifers, but the heterogeneity of karst aquifers poses a real challenge in conventional well logging. Borehole geophysics presents several tools that may be applied to the characterization of heterogeneous karst aquifers: (1) Image and flow logs provide detailed information about the nature of hydraulically active zones intersected by boreholes; (2) Geometric correlation of logs between boreholes indicates possible connections between the zones in separate boreholes; (3) Water-quality and hydraulic-head data derived from logs can be used to identify subsurface flow paths; (4) Cross-borehole flow experiments can be used to infer the properties of hydraulic connections among subsurface conduits; and (5) Geophysical measurements can be made at local, intermediate, and large scales to infer the relation between scale and hydraulic conductivity. Examples of these applications are given for karst or karst-like aquifers at sites in Arizona, Illinois, Kentucky, New Hampshire, and Florida, demonstrating the specific contributions that borehole geophysics can make in karst characterization.

INTRODUCTION

Borehole geophysical logging is a commonly used technique for the in situ characterization of aquifers. However, heterogeneous karst aquifers are difficult to describe using data obtained in a limited number of boreholes. Although the logs provide detailed information about formation properties in the immediate vicinity of boreholes, one can never expect to drill enough boreholes to characterize karst flow systems on the basis of borehole data alone. Boreholes cannot sample enough of the heterogeneous subsurface openings to provide a representative sample of distribution of permeability because of the variability of the fractures, bedding planes, and vugs connected to form flow paths. This paper describes a number of ways in which geophysical measurements in boreholes can be combined with other data to mitigate the severe challenges presented by the need to characterize karst flow systems. Each of these is illustrated by a specific example. Further development of these techniques will be needed to improve the ability to characterize karst aquifers using the available borehole characterization technology.

IDENTIFYING HYDRAULICALLY ACTIVE ZONES

Most geophysical logs provide precise information about the in situ properties of subsurface formations but in the form of measurements such as gamma activity or electrical conductivity that are only indirectly related to hydraulic parameters of interest. Previous results generally indicate that the transmissivity of bedding planes, fractures, and solution openings cannot be inferred from the appearance of those features on borehole image logs or the apparent aperture of those features on caliper logs (Paillet, 1998). Recently developed high-resolution flow logging equipment such as the heat-pulse (Hess, 1986) and electromagnetic (Molz and others, 1994) flowmeters add the important ability to tie borehole hydraulics to geophysical log data. An example is illustrated in figure 1 for a massive limestone aquifer in northern Arizona. The geophysical logs indicate the precise depths where water exits the borehole during steady injection. The outflow points can be associated with features on the other logs that represent the hydraulically conductive features in the vicinity of the borehole. In figure 1, these features include fractures, bedding planes, and a small cavern. Although the full set of logs provides no information about how far these features extend away from the borehole, the flow log does allow some analysis of the limited set of features where flow actually occurs. This is an important step beyond simply identifying the fractures and solution features that intersect boreholes.

CORRELATION OF ZONES BETWEEN BOREHOLES

In Eve L. Kuniansky, editor, 2001, U.S. Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 01-4011, pp. 116-123

One possible approach in understanding how hydraulically conductive fractures, bedding planes, and solution openings identified in boreholes are connected to form flow systems is to project these features in the regions between boreholes. This seems simple in principle, but becomes difficult in practice when there are many possibly permeable features in each borehole and boreholes are located far apart. Spatial correlation on the basis of appearance in image logs and occurrence at similar depths is generally not effective. A much more effective approach is to locate permeable openings with respect to sedimentary structure. For example, inflow to or outflow from a series of boreholes in northern Illinois was associated with solutionally enlarged bedding plane openings (fig. 2). Many such bedding planes intersected each borehole, but only a few conducted most of the flow (Paillet and Crowder, 1996). The correlation of these bedding planes was established over borehole separations of about a kilometer by correlating gamma logs. The gamma correlation established the strike and dip of bedding so that borehole elevation and the regional dip could be used to define the precise stratigraphic position of the bedding planes in each borehole. This structural correlation showed that sets of bedding planes served as regional conduits, but that the most transmissive bedding plane within sets of closely-spaced planes varied from one borehole to the next. The combination of structural correlation and flow log analysis can be useful in identifying how solution openings are organized into continuous flow paths even when large-scale hydraulic test data are not available.

IDENTIFYING FLOW PATHS AND COMPARTMENTS

Although structural correlation of solution features on the basis of aquifer geometry is a useful technique, there are other physical/chemical ways to identify how solution openings identified in individual boreholes might be connected in the regions between boreholes. These techniques include methods that identify the chemical or hydraulic-head signatures of aquifer zones. For example, gross chemical signature measurements of zones can be made in open boreholes. Examples of such open-borehole water chemistry techniques are given by Paillet and Pedler (1996) and Tsang and others (1990). Flowmeter logging provides a technique for determining the hydraulic head of individual zones using the numerical flow model inversion of Paillet (1998, 2000). Figure 3 illustrates an example where the flow modeling technique is used to quantify the hydraulic heads of the three different solution openings contributing flow to a borehole. Proper application of either the water-quality or hydraulic-head techniques involves the measurement of fluid column electrical conductivity or borehole flow under at least two different quasi-steady borehole flow conditions. In each case, correlation of water quality or hydraulic head between boreholes can be used to identify large-scale flow paths in karst aquifers.

CROSS-BOREHOLE FLOW EXPERIMENTS

Suspected connections along flow paths between boreholes can be characterized using the cross-borehole flow method described by Paillet (1998). The transient flow response at selected positions in an observation borehole can be used to identify the hydraulic properties of the flow path between the depths where that path intersects the two boreholes. A simple example is shown for a shallow, karst-like flow path between boreholes in granitic rock in New Hampshire in figure 4. In this example, the water-producing zone in each of four boreholes can be identified. Although hydraulic-head measurements clearly show that this one zone is connected to all four boreholes, the water-producing zones appear very different in each case. The image log interpretations (fig. 4A) vary from clean, steeply dipping fractures to highly altered and enlarged openings of no particular orientation. Simple spatial correlation suggests a sub-horizontal zone of permeability. A cross-borehole experiment shows that the flow induced in an observation borehole after a pump is turned on in one of the other boreholes precisely matches the type curve for a single infinite planar opening of specified transmissivity and storage coefficient (fig. 4B). This kind of information could not have been derived from the combined analysis of the images and geophysical properties of the individual water-producing features at the four places where they intersect individual boreholes. Such cross-borehole flow experiments provide a useful way to characterize the properties of flow paths connecting boreholes after other analysis has identified the existence of such connections.

INTEGRATING MULTIPLE-SCALE DATA

Even in the most well-funded karst studies, there is unlikely to be enough drilling to characterize flow paths using the combination of flow logging, stratigraphic correlation, and cross-borehole flow testing. Non-invasive surface geophysical soundings can provide the area-wide coverage needed to fully characterize the subsurface. There are commonly two serious problems with using these soundings: 1) Sounding interpretations can be ambiguous; and 2) Subsurface flow depends on such factors as flow boundary conditions that cannot be derived from images of aquifer geometry alone. The combination of limited fine-scale, definitive data from boreholes and large-scale but ambiguous data from surface geophysics can serve to resolve the ambiguity by eliminating alternative models for geophysical interpretation and by relating subsurface hydraulic conditions to measured aquifer properties. For example, Paillet and others (1999) and Paillet and Reese (2000) used electromagnetic sounding profiles to characterize a shallow carbonate aquifer in south Florida. Aquifer units and regional hydraulic gradients were identified using borehole log data. These local aquifer units identified at drilling sites were then extended into the approximately 10 kilometers separations between boreholes using time domain electromagnetic (TEM; Fitterman and Stewart, 1986) soundings. The expected ambiguity in sounding interpretation was resolved by using soundings near boreholes to relate TEM interpretation models to the subsurface conductivity values (fig. 5). These results could be used to (1) eliminate alternate but otherwise equivalent interpretation model geometry; and (2) identify the spatial resolution in the TEM data set. Further development of the integrated analysis of surface geophysical soundings with geophysical, geologic, and hydrologic data from boreholes appears to be the only effective way to completely characterize karst terrain over the full range from local-borehole (1 meter or less) to site-wide (1 kilometer or more) scales.

CONCLUSIONS

Geophysical measurements in boreholes provide useful information about subsurface aquifers, but the heterogeneity of karst aquifers poses a real challenge in conventional well logging. Borehole geophysics presents several tools that may be applied to this fundamental problem. Image and flow logs provide detailed information about the nature of hydraulically active zones intersected by boreholes that can be used to infer how these zones fit into regional hydrogeology. Geometric correlation of logs between boreholes indicates possible connections between zones in the regions between boreholes. Water-quality and hydraulic-head data derived from logs can be used to identify possible hydraulic connections between subsurface flow paths. Cross-borehole flow experiments can be used to infer the properties of hydraulic connections among subsurface conduits. Geophysical measurements can be made at local, intermediate, and large scales to infer the relation between scale and hydraulic conductivity. Examples of these applications show how they contribute to the characterization of karst or karst-like aquifers at sites in Arizona, Illinois, Kentucky, New Hampshire, and Florida, demonstrating the specific contributions that borehole geophysics can make in karst characterization.

REFERENCES

Fitterman, D.V., and Stewart, M.T., 1986, Transient electromagnetic sounding for groundwater: Geophysics, v. 51, no. 4, p. 995-1005.

Hess, A.E., 1986, Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter: Canadian Geotechnical Journal, v. 23, no. 1, p. 69-78.

Molz, F.J., Bowman, G.K., Young, S.C., and Waldrop, W.R., 1994, Borehole flowmeters--field application and data analysis: Journal of Hydrology, v. 163, p. 347-371.

Paillet, F.L., 1998, Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations: Water Resources Research, v. 34, no. 5, p. 997-1010.

Paillet, F.L., 2000, A field technique for estimating aquifer parameters using flow log data: Ground Water, v. 38, no. 4, p. 510-521.

Paillet, F.L., and Crowder, R.E., 1996, A generalized approach for the interpretation of geophysical well logs in ground water studies--Theory and application: Ground Water, v. 34, no. 5, p. 883-898.

Paillet, F.L., Hite, Laura, and Carlson, Matt, 1999, Integrating surface and borehole geophysics in ground water studies - an example using electromagnetic soundings in south Florida: Journal of Environmental and Engineering Geophysics, v. 4, no. 1, p. 45-55.

Paillet, F.L., and Pedler, W.H., 1996, Integrated borehole logging methods for wellhead protection applications: Engineering Geology, v. 42, p. 155-165.

Paillet, F.L., and Reese, R.S., 2000, Integrating borehole logs and aquifer tests in aquifer characterization: Ground Water, v. 38, no. 5, p. 713-725.

Tsang, C.F., Hufschmied, P., and Hale, F.V., 1990, Determination of fracture inflow parameters with a borehole fluid conductivity method: Water Resources Research, v. 26, no. 4, p. 561-578.

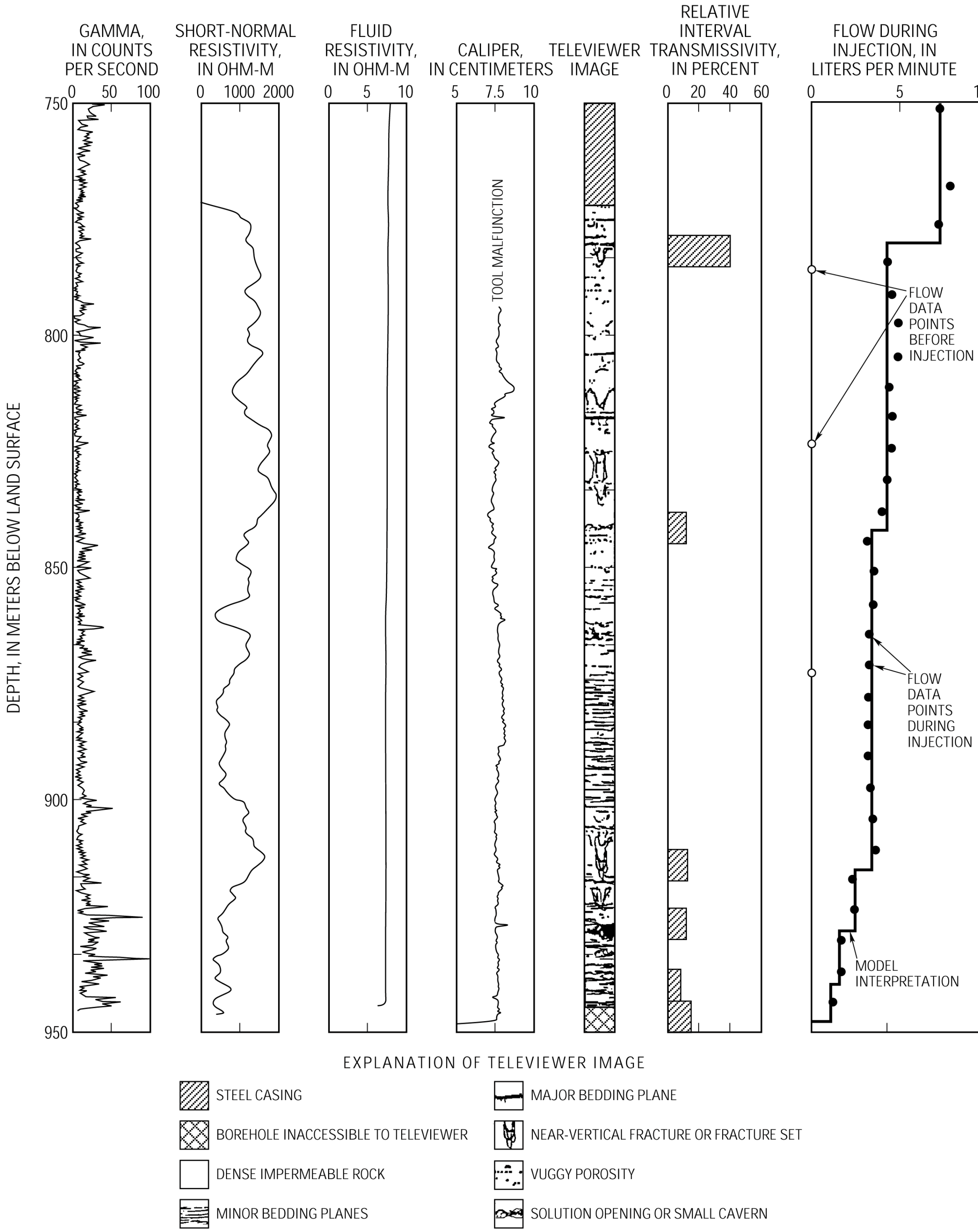


Figure 1–Composite of gamma, short-normal resistivity, fluid column resistivity, caliper, and televiewer logs compared with a borehole flow profile obtained with a heat-pulse flowmeter during injection in a borehole in fractured and bedded limestone in northern Arizona; data from Paillet (1998).

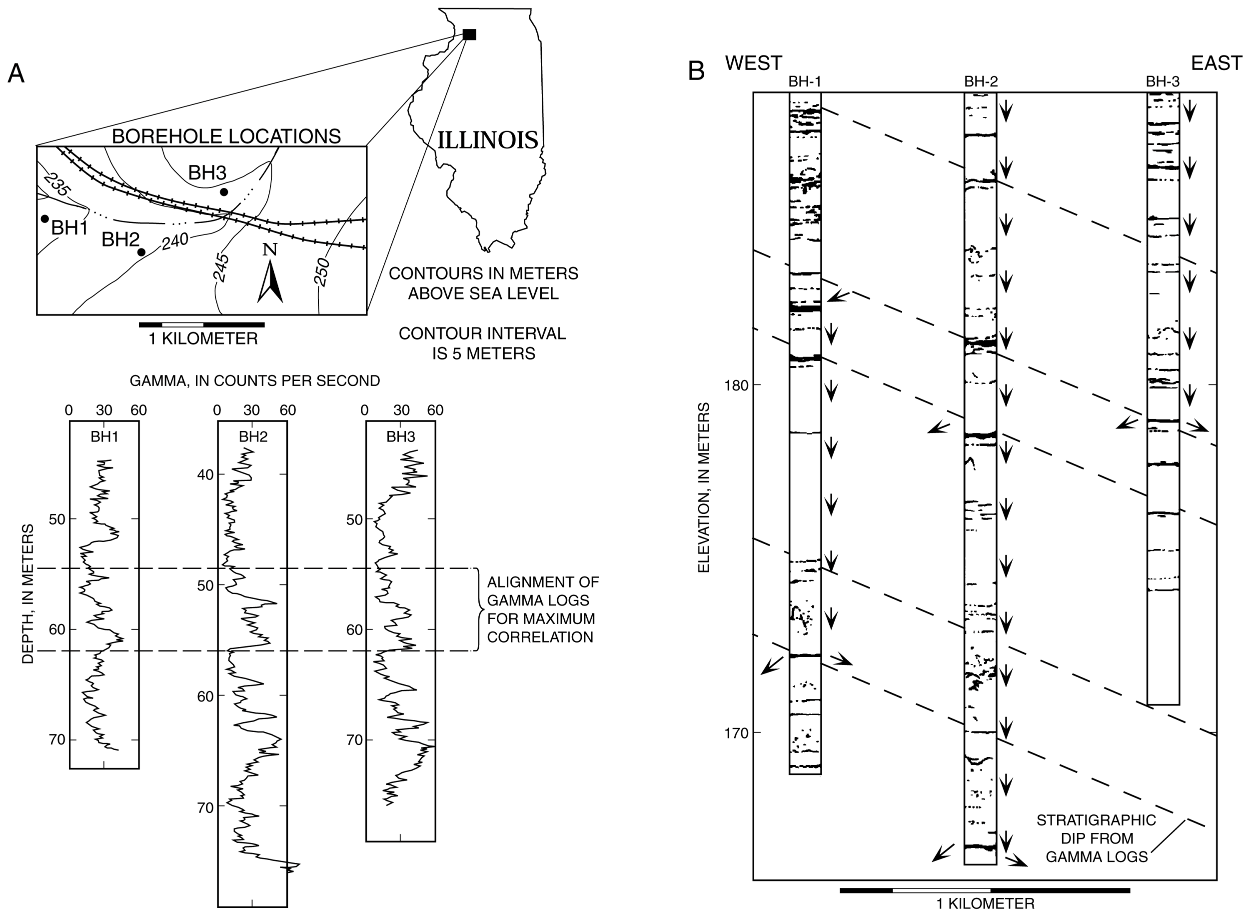
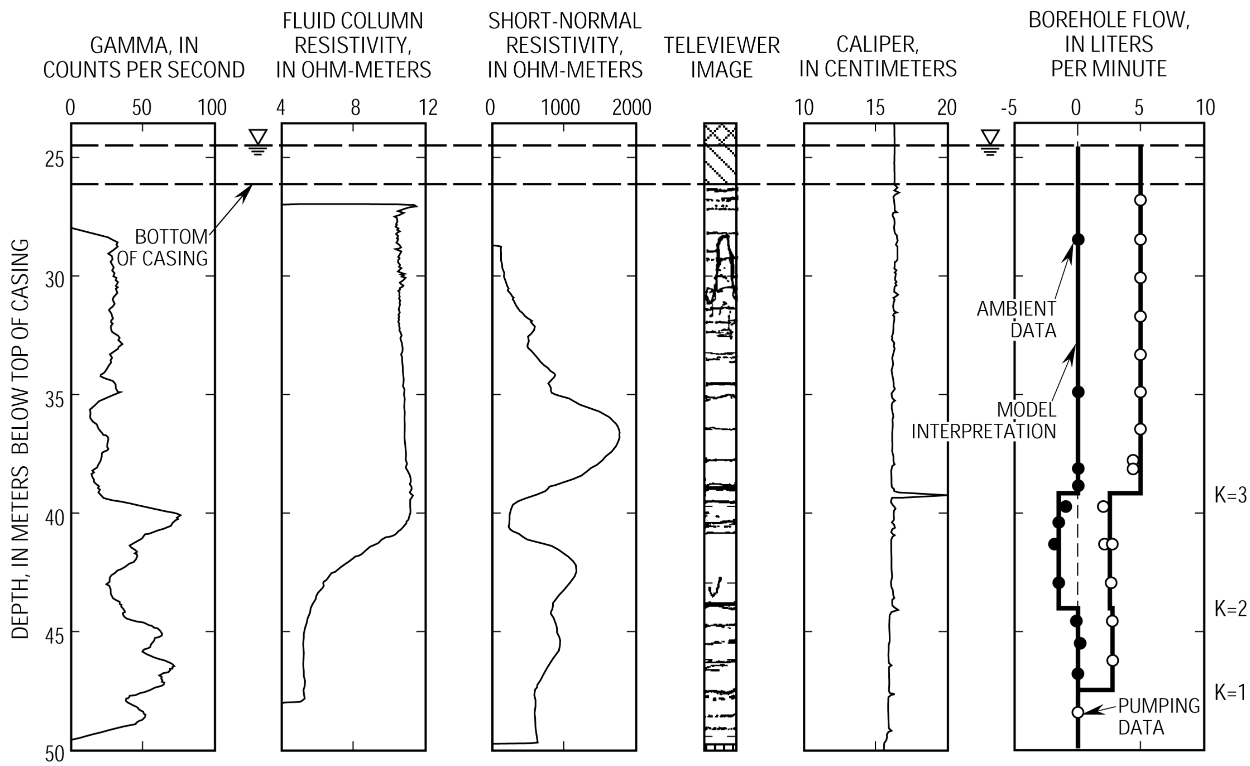


Figure 2–A) Horizontal alignment of gamma logs along an east-west profile used to identify stratigraphic dip in a dolomite aquifer in northern Illinois; and B) Televiewer logs, stratigraphic correlations, and flowmeter information used to identify continuous bedding planes and aquifer flow zones where arrows indicate direction of ambient flows measured in boreholes and locations of inflow and outflow; from Paillet and Crowder (1996).



FLOW MODEL INTERPRETATATION

ZONE NUMBER	DEPTH (METERS)	TRANSMISSIVITY ($10^{-5}m^2/s$)	HYDRAULIC HEAD (m BELOW REFERENCE)
3	39.0	5.0	24.6
2	43.5	5.0	25.8
1	47.0	10.0	25.5

Figure 3–Composite of gamma, fluid column resistivity, short-normal resistivity, televiewer, and caliper logs compared with flow profiles obtained under ambient and pumped conditions in fractured and bedded limestone in south-central Kentucky; data from Paillet (2000).

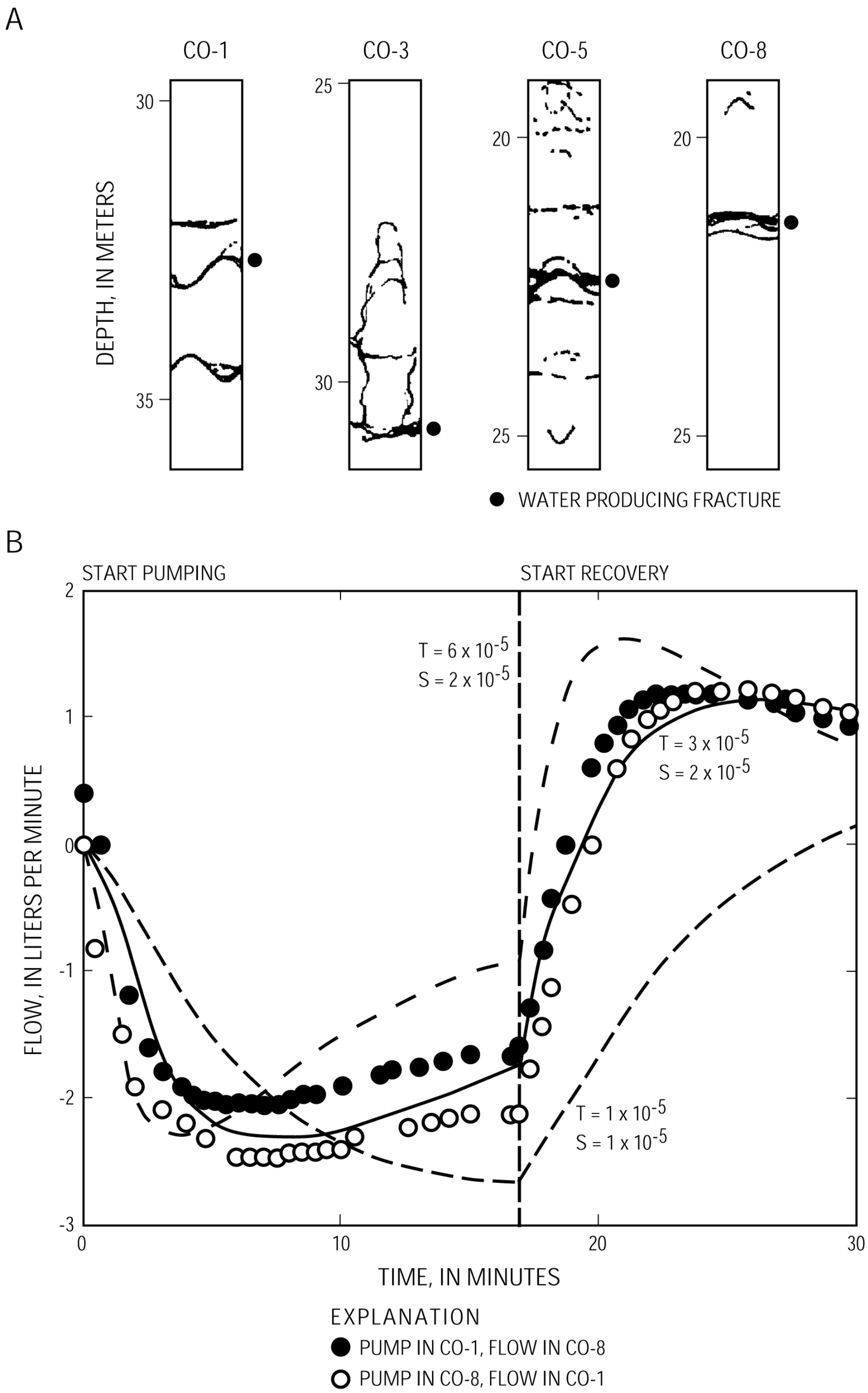


Figure 4–A) Televiewer logs of altered, water-producing fracture zones in granitic schist at a site in central New Hampshire; B) A cross-borehole flow experiment, where flow is measured above a fracture zone in one borehole while a pump is turned on and off in an adjacent borehole, shows that the fracture zone containing these features can be modeled as a single horizontal fracture of uniform transmissivity (T) and storage coefficient (S); modified from Paillet (1998).

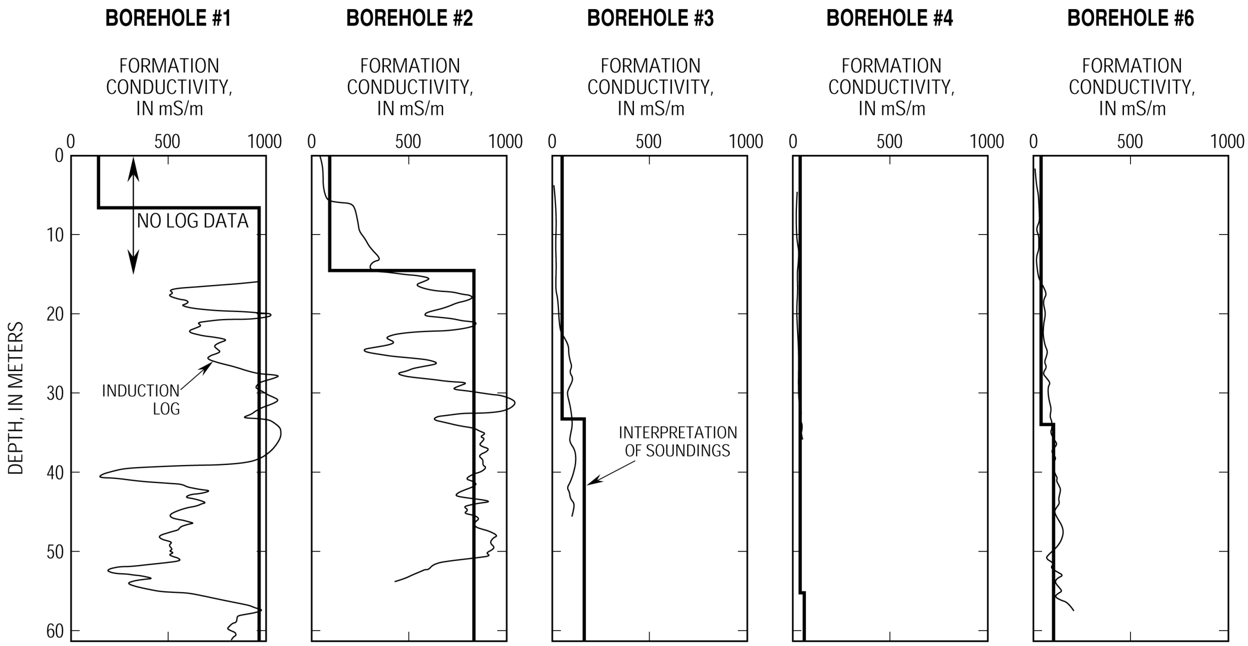


Figure 5–Two-layer interpretations of electromagnetic soundings made adjacent to boreholes with induction logs; these data were used to identify the appropriate inversion model for the projection of aquifers between borehole sites as described by Paillet and others (1999).