Geophysical characterization of fractured rock aquifers: Accounting for scale effects and putting hydrology in the geophysics

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Abstract

Characterization of fractured-bedrock aquifers is one of the most difficult problems in hydrogeology. Successful characterization of aquifers at the site scale requires the effective integration of the three basic tools at our disposal: 1) surface geophysical soundings provide full non-destructive coverage of the aquifer volume but are generally ambiguous in interpretation and fail to identify individual fracture conduits; 2) geophysical measurements in boreholes can characterize fractures in detail but only adjacent to individual boreholes; and 3) hydraulic measurements in boreholes can be used to generate direct relationships between geophysical and hydraulic properties for the rock immediately adjacent to the borehole. The most common drawback of surface geophysical soundings is the ambiguity that results when regions of anomalous response might be related to fracture permeability, but may also be attributed to alteration, rock texture, or lithology. In contrast, several different geophysical properties can be measured using a conventional suite of geophysical well logs. These data can be used to generate site-specific interpretation models that relate a specific geophysical sounding response to several independent rock properties. A quantitative relation between the geophysical log parameters (gamma activity, resistivity, acoustic velocity, etc.) and the hydrologic properties of the formation (permeability, storage, and water quality) can be defined by regressing hydraulic measurements in the borehole versus the geophysical properties of the appropriate intervals. In the past, these regressions were accomplished using cumbersome and time-consuming straddle-packer isolation methods, or by conducting laboratory experiments using small core samples from intervals where such samples can be recovered. Relatively new, high-resolution flowmeter and borehole-dilution logging techniques offer more readily available and more flexible methods for relating borehole hydraulics to geophysical properties. This report provides specific examples of studies at fractured-bedrock aquifer sites where geophysical and hydraulic measurements are effectively integrated using this combination of techniques.

Introduction

Fractured bedrock aquifers offer one of the most challenging characterization problems in hydrogeology. The physical properties of fractured-rock aquifers are well understood in principle. If the geometry and hydraulic properties of the fracture network are specified, the flow and dispersion in such aquifers can be predicted. Of course, these properties are not known in detail for most fracture-rock aquifers. The obvious recourse is to sample subsurface conditions using boreholes. The inherent complexity of fractured aquifers and the dependence of hydraulic properties in these aquifers on the scale of investigation mean that it is impractical to expect complete characterization by borehole investigations alone. Surface geophysical soundings provide the ability to fully sample the aquifer volume over the dimensions of interest. However, these soundings rarely provide enough resolution to delineate individual fracture flow conduits. Geophysical soundings are also inherently ambiguous because any one geophysical property is related to several different rock mass properties such as lithology, alteration, permeability, and solute content. These considerations lead to the obvious conclusion that effective characterization of fractured bedrock aquifers depends on the integration of different kinds of data at different scales of investigation so as to: 1) determine the relation between aquifer properties and scale of investigation by comparing measurements spanning the spatial scale of interest; and 2) relate the geophysical and hydraulic properties of the aquifer through empirical or model-based relationships by comparing geophysical and hydraulic data at borehole locations.

THE VIRTUAL TOOL BOX

Although aquifer investigation cannot be completed on the basis of borehole data alone, measurements in boreholes provide the key to both scale effects and the relationship between physical and hydraulic properties. Previous geophysical studies of fractured rocks cite the application of a “tool box” of different investigation techniques such that the most effective method can be selected from among the various tools (Long et al, 1996).

There is an analogous "virtual toolbox" of analysis techniques that can be applied to fractured-rock aquifer investigation (Paillet, 2002). One such conceptual tool is the direct comparison of the same measurement made at very different scales. For example, geophysical measurements can be made at different scales of investigation in the form of surface soundings and borehole logs. Another conceptual tool involves these same measurements to address a second important problem: the multivariate nature of geophysical measurements. Although any one measurement usually depends on more than one rock property, geophysical logs are readily obtained in suites of several different (electrical, acoustical, nuclear, etc) measurements. Well-log data thus provide a direct way to relate any geophysical sounding to rock properties of interest by using multiple measurements to develop multivariate models for geophysical response. Such methods might be used to determine whether the properties of zones of anomalously low electrical resistivity in a rock mass are related to lithology, alteration, or ground-water salinity. In almost all published studies, the geophysical anomalies associated with hydraulically-conductive fracture zones are found to be: 1) difficult to distinguish from similar anomalies associated with lithologic contacts; and 2) attributed to the physical properties of alteration minerals and clay films lining fracture faces rather than hydraulic conductivity (Keys, 1979; Nelson et al, 1983; Long et al, 1996).

Probably the most important issue in the geophysical investigation of fractured-rock aquifers is the need to relate geophysical properties that are not of inherent interest to hydraulic properties that are of interest. In the past, this important link was made by comparing well logs with measurements made over discrete borehole intervals using straddle-packer isolation systems. Straddle-packer hydraulic tests and sampling remain the "gold standard" of hydrogeology (Hsieh et al, 1993; Long et al, 1996). However, several new high-resolution flow logging techniques such as heat-pulse (Hess, 1986) and electromagnetic (Molz et al, 1994) flowmeter logging and borehole dilution methods (Tsang et al, 1990) provide more cost effective and flexible methods for putting the hydrology into the geophysical investigation. A typical example is illustrated in figure12, where a flowmeter log run under injection conditions indicates the relative permeability associated with specific borehole wall openings displayed on televiewer and caliper logs for a deep karst aquifer.

One of the most important attributes of high-resolution borehole flow logging is that all logs can be run as part of the same operation. This avoids the possibility of trying to compare straddle-packer measurements made under one hydraulic condition with geophysical logs run at another time under other conditions. This is a real and persistent problem in wellhead protection or contaminant dispersal studies in areas with active production or remediation wells. Mass-balance methods can be used to quantify water sample properties from contributing zones (Paillet and Thomas, 1996). Although these are important advances in fractured aquifer characterization, flow logging is not a complete substitute for straddle-packer investigations (Molz et al, 1989). Flowmeter and dilution methods are performed in open boreholes, so that 1) large volumes of water need to be purged for effective sampling; and 2) open borehole measurements involve different boundary conditions than those for discrete zones in isolation. Borehole logging measurements always involve some degree of measurement error. This means that contributions from less productive zones may not be identified in the presence of the most transmissive zones in a borehole. The most efficient and effective characterization of fractured rock aquifers results when borehole flow logging methods are combined with a carefully designed straddle-packer test program based on a preliminary analysis of the borehole log data (Paillet, 1995; Long et al, 1996).

Examples Of Fractured Rock Characterization

Quantitative estimates of fracture transmissivity can be obtained using borehole flow modeling techniques (Paillet, 1998; 2000). In figure 2, borehole flow logs were obtained under two different hydraulic conditions: ambient and steady pumping. The model analysis gives a unique fit to the data for a set of hydraulic values (transmissivity and zone water level) that matches the observed flow under the two conditions and accounts for the net change in water level (drawdown) produced by the pumping (table1). Comparison of flowmeter model results to straddle-packer hydraulic tests in the same borehole show that there is at most two orders of magnitude of sensitivity in the analysis (figure 3). In figure 3A, the flow model analysis predicts the transmissivity of fractures and fracture zones as long as the zones are among the top two orders of magnitude in transmissivity. The less transmissive zones are not characterized in the flow log interpretation even when they are found to have a low but detectable transmissivity when isolated with straddle packers. Significant discrepancies between open borehole and straddle-packer hydraulic tests can sometimes occur (figure 3B). In this example, there are several minor fractures connected to a large fracture near the bottom of the borehole. Under open borehole conditions, almost all flow enters the borehole through the main fracture. However, when one or more of the adjacent fractures are isolated with packers, hydraulic tests indicate the transmissivity of the large fracture to which these minor fractures are connected.

Cross Borehole Methods

One approach to characterizing the large-scale response of fractured aquifers is to conduct multi-borehole aquifer tests. Conventional test analysis methods based on open-borehole water level measurements cannot be applied if there are several different fracture flow-path aquifers present. Tests can be conducted by laboriously isolating zones in each borehole with straddle-packer equipment. If there are a number of major, possibly permeable fractures in each borehole, this approach can become especially cumbersome. For example, if there are an average of N fractures in each of 3 boreholes, the number of separate hydraulic tests is N cubed. The geometry of the fractures (stratigraphic correlation, projection of local strike and dip, etc.) may provide hints about large-scale connections (Paillet et al, 1987). A more effective approach is to conduct cross-borehole flowmeter tests where cycles of pumping are applied to one borehole and flow measured in an adjacent borehole (Paillet, 1998; Williams and Paillet, 2002). This method can be used to identify the large-scale flow connections for more detailed characterization using straddle-packer hydraulic tests, tracer tests, or well completion and monitoring.

The cross-borehole flowmeter analysis is based on the recognition of classes of flow response (type curves) associated with specific classes of fracture flow path connections, and then quantitative modeling to estimate the transmissivity and storage coefficient of the discrete fractures within the network. A typical example (figure 4) illustrates a hydraulic connection between four boreholes where water-producing zones in each borehole appear as fractures of very different orientation. The cross-borehole flow analysis indicates that the fracture network can be modeled as a simple horizontal fracture connecting the boreholes. Thus, the fracture zone responds as if a single large-scale horizontal fracture-zone aquifer is composed of individual, randomly orientated fractures intersecting individual boreholes. This confirms the results of previous studies at this site (Hardin et al, 1987).

A contrasting example shows a situation where a single horizontal fracture appears to intersect two boreholes, but the fracture response cannot be fit to the single-fracture type curve (figure 5). Two boreholes in a fractured-granite aquifer produce water from a fracture at about 60 m in depth. The image log of the fracture appears horizontal in each borehole, and similar water level elevations in the boreholes indicate a direct hydraulic connection. A cross-borehole flow experiment shows the general kind of response expected for a horizontal connection, where pumping in one borehole produces downflow in the other borehole. The downflow reaches a peak about 20 minutes after the start of pumping and then declines. However, the single-fracture model indicates that the response on recovery should be the exact mirror image of the response to pumping (Lapcevic et al, 1993). This is clearly not the case in figure 5, because a single-fracture model with a transmissivity of about 4×10^{-5} m^2/s matches the pumping response (upper panel), but a value of about 4×10^{-6} m^2/s matches recovery (lower panel). The striking asymmetry of the cross-flow response indicates that some sort of conduit connects the two boreholes, but that the response is definitely not that of a simple, horizontally-uniform fracture. One possible cause for this response would be a channel embedded in the fracture face and connecting the two boreholes in an otherwise uniform and much lower transmissivity fracture.

Wireline Packer

In some situations project objectives may require that fractures be isolated with packers for most effective hydraulic measurements or water sampling. A wireline-operated packer system can be used in conjunction with other borehole logging to provide packer test results at the time of logging (figure 6). The packer is designed to provide separation of the borehole into two zones so that the upper zone can be monitored by conventional slug-test and water-sampling methods, and a differential pressure transducer in the probe measures the hydraulic head in the zone below the packer. This configuration allows rapid reconnaissance of the borehole by systematically “splitting the difference” between potential inflow zones. The wireline packer is thus a compromise between the need to sample from hydraulically isolated zones and the need to perform rapid and efficient profiling of the borehole at the time of logging and under the hydraulic regime prevailing at the time of logging. Numerical methods are used to convert the sequence of single-packer water level and sample data to equivalent straddle packer results for the zones in intervals between stations where measurements were made (Paillet et al, 1998).

The Borehole Boundary Layer

In almost all fractured-aquifer studies related to water supply development or site remediation, hydrologists are interested in predicting the movement of water and solute through the rock mass, and not the rate of flow in individual fractures. However, almost all data is derived from boreholes where individual fractures conduct flow into or out of the borehole during hydraulic tests. It is theoretically possible to measure the properties of a representative sample of individual fractures so that a predictive model can be created for a particular aquifer. In practice, it is unlikely that enough fractures can be characterized in individual boreholes to create such a model. One of the fundamental problems in collecting hydraulic data from boreholes in fractured-rock aquifers is the separation of effects related to individual fractures conducting flow into the borehole from the large-scale properties of the aquifer to which those fractures are connected.

The borehole flow model (Paillet, 1998; 2000) provides a useful technique for the effective correction of borehole hydraulic data to account for the influence of local fracture connections. Conceptually, this is equivalent to correcting seismic data for the frequency response of the geophones used to collect the data. The application of the flow model is illustrated in figure 7. The borehole is assumed to be connected to the site-scale aquifer by an annular boundary region. When hydraulic tests are conducted in the borehole, flow into or away from the borehole is influenced by the radial geometry. The geometric convergence or divergence of the flow field causes a local change in hydraulic head that “translates” the water level in the borehole to the hydraulic head in the local aquifer. If the discrete fracture connecting the borehole to the surrounding aquifer has a relatively large permeability, the transient response of the fracture and borehole storage will have a negligible effect on the interpretation of hydraulic head changes in the far-field aquifer. In many situations, the fractures connecting the borehole to the aquifer will have permeabilities significantly less than those of the most permeable fracture zone or zones that determine the large-scale transport properties of the aquifer at the site scale. Thus, scale effects often cause the hydraulic response of individual fractures to influence or even dominate experiments intended to characterize the properties of the large-scale aquifer system.

The concept illustrated in figure 7 shows how the effects of individual fractures can be removed from open-borehole data sets. The method is based on using a borehole flow model to relate flow and open borehole water level to the hydraulic conditions at the outer boundary of the annular region around the borehole. The simplest approach is to use the flow model to relate flow measured between individual fractures in the borehole to the hydraulic head of the large-scale aquifer at the “outer edge” of the boundary region in figure 7. This effectively removes the local flow loss associated with the movement of water into or out of the borehole from the drawdown in the large-scale aquifer. Examples of the technique used to infer the large-scale structure of aquifers are given by Paillet (2001) and Paillet et al (2000).

Conclusions

Successful characterization of fractured-bedrock aquifers at the site scale requires the effective integration of the three basic tools: surface geophysical soundings provide full non-destructive coverage of the aquifer volume but are generally ambiguous in interpretation and fail to identify individual fracture conduits; geophysical measurements in boreholes can characterize fractures in detail but only adjacent to individual boreholes; and hydraulic measurements in boreholes can be used to generate direct relationships between geophysical and hydraulic properties. The most common drawback of surface geophysical soundings is the ambiguity that results when regions of anomalous response might be related to fracture permeability, but may also be attributed to alteration, rock texture, or lithology. In contrast, several different geophysical properties can be measured using a conventional suite of geophysical well logs. These data can be used to generate site-specific interpretation models that relate a specific geophysical sounding response to several independent rock properties. A quantitative relation between the geophysical log parameters (gamma activity, resistivity, acoustic velocity, etc.) and the hydrologic properties of the formation (permeability, storage, and water quality) can be defined by regressing hydraulic measurements in borehole intervals to the geophysical properties of the appropriate intervals. In the past, these regressions were accomplished using cumbersome and time consuming straddle packer isolation methods, or by conducting laboratory experiments using small core samples from intervals where such samples can be recovered. Relatively new, high-resolution flowmeter and borehole dilution logging techniques offer more readily available and more flexible methods for relating borehole hydraulics to geophysical properties.

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Fred Paillet joined the department in Maine after retiring from the U. S. Geological Survey in 2002. Before then he was chief of the Borehole Geophysics Research Project and conducted studies in all aspects of borehole geophysics applied to ground water. He has published numerous papers on the use of geophysical logs and borehole flowmeter data in the characterization of fractured bedrock aquifers.

Table 1 – Results of flow model fit to flow log data in figure 2 for the Connecticut bedrock borehole

FLOW ZONE (depth in meters)	TRANSMISSIVITY (meters squared per second)	ZONE HYDRAULIC HEAD (meters below top of casing)
16.8	2.0×10^{-5}	5.95
32.0	4.0×10^{-5}	6.87
39.8	1.3×10^{-5}	6.87

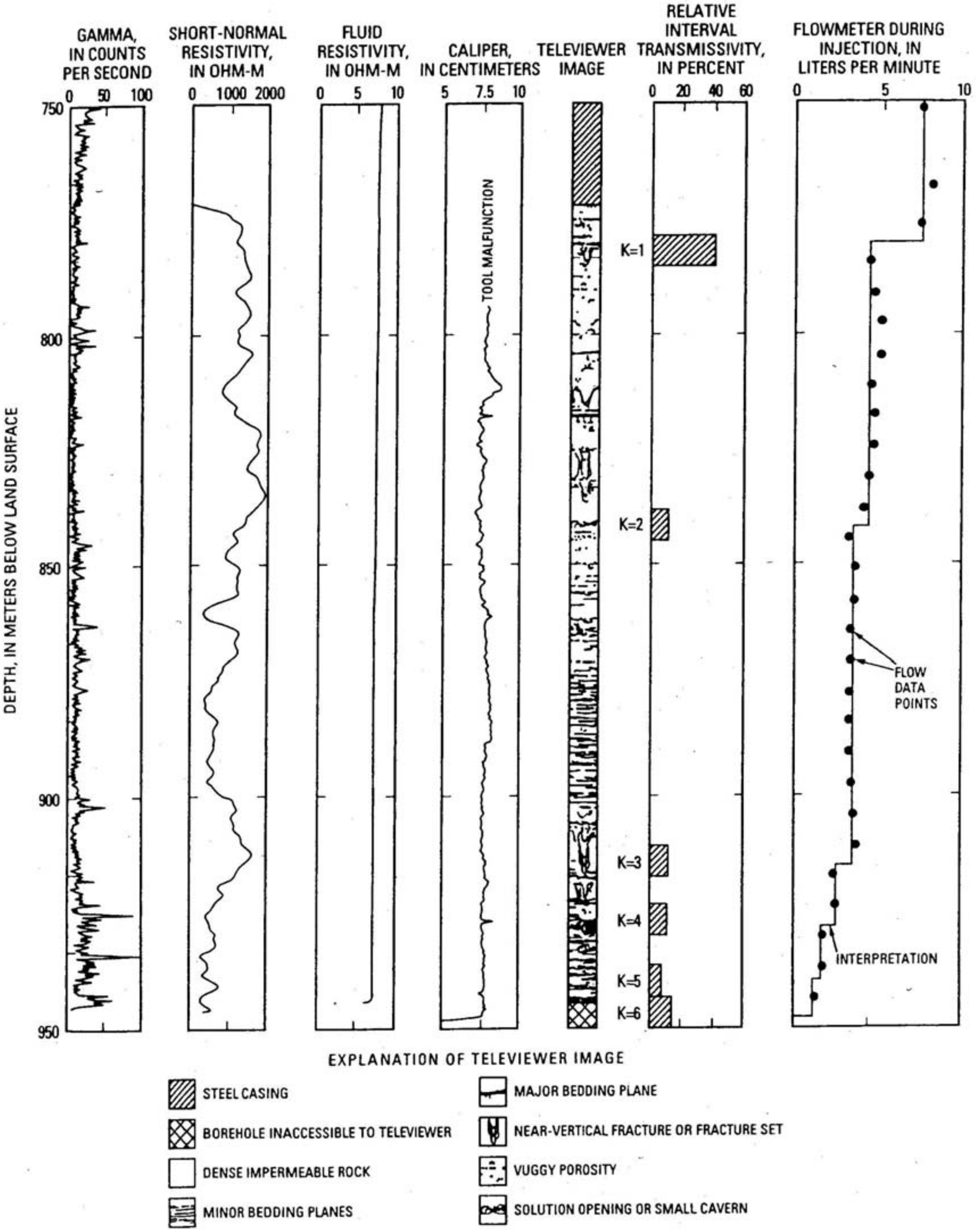

Figure 1 – Example of borehole flow logging under steady injection conditions to estimate the relative inflow from fractures and borehole wall openings indicated on televiewer and caliper logs (from Paillet, 1998).

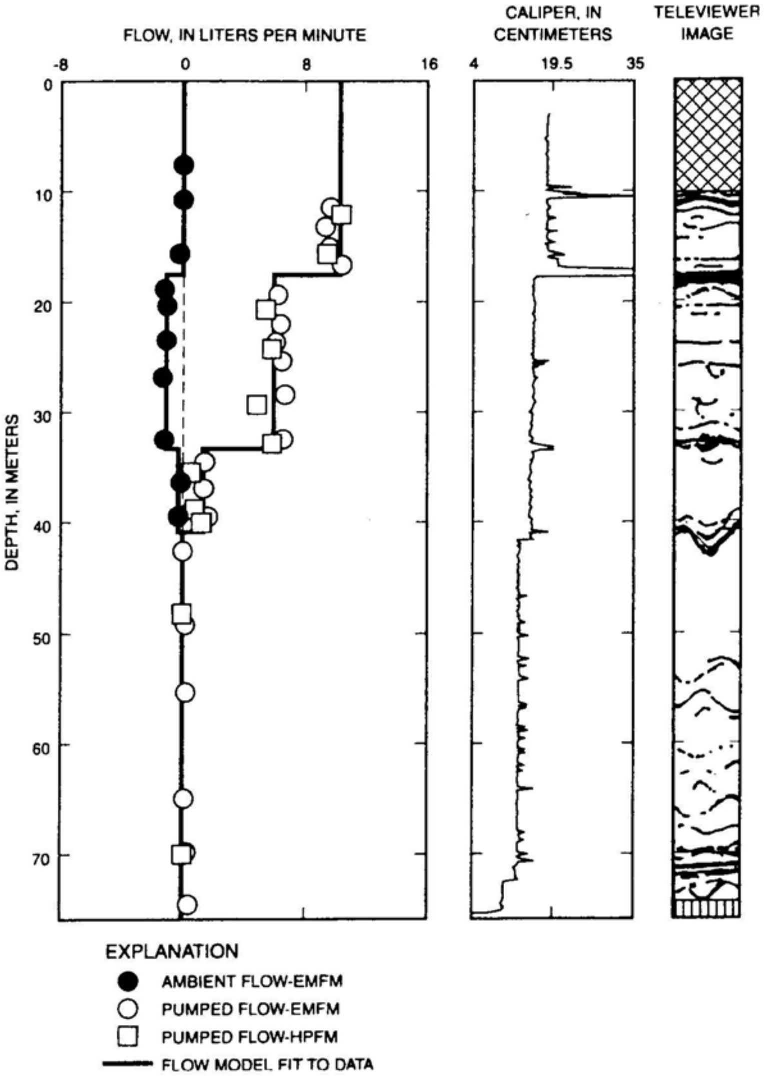

Figure 2 – Example of borehole flow model application to the interpretation of the hydraulic properties (transmissivity and zone water level; table 1) of fractures intersecting a borehole (from Paillet, 2004).

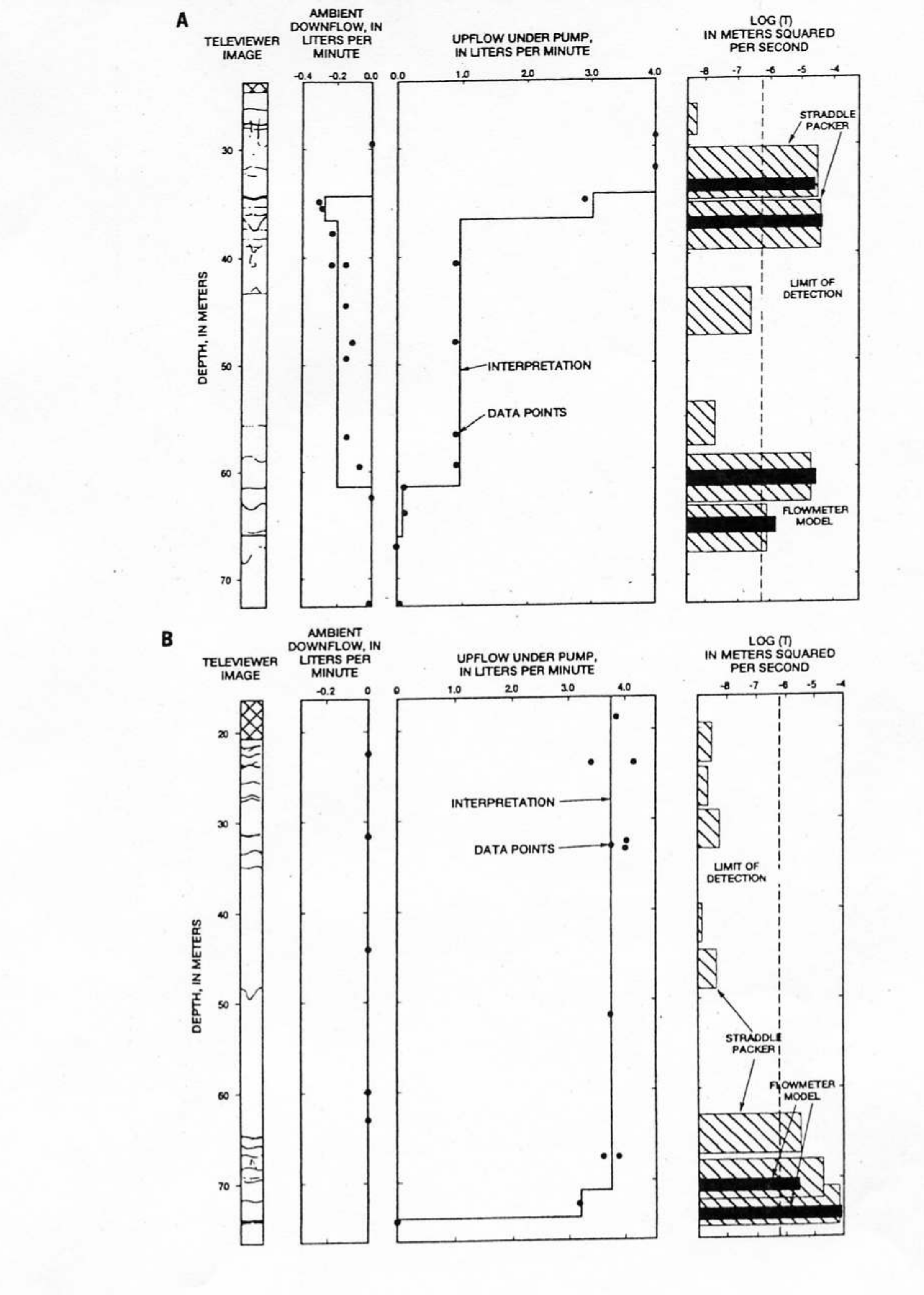

Figure 3 – Comparison of fracture transmissivity interpreted from borehole flow model analysis to values given by conventional straddle packer tests for A) A borehole where there is good agreement between the data sets; and B) A borehole where hydraulic boundary conditions cause the data sets to differ (from Paillet, 1998).

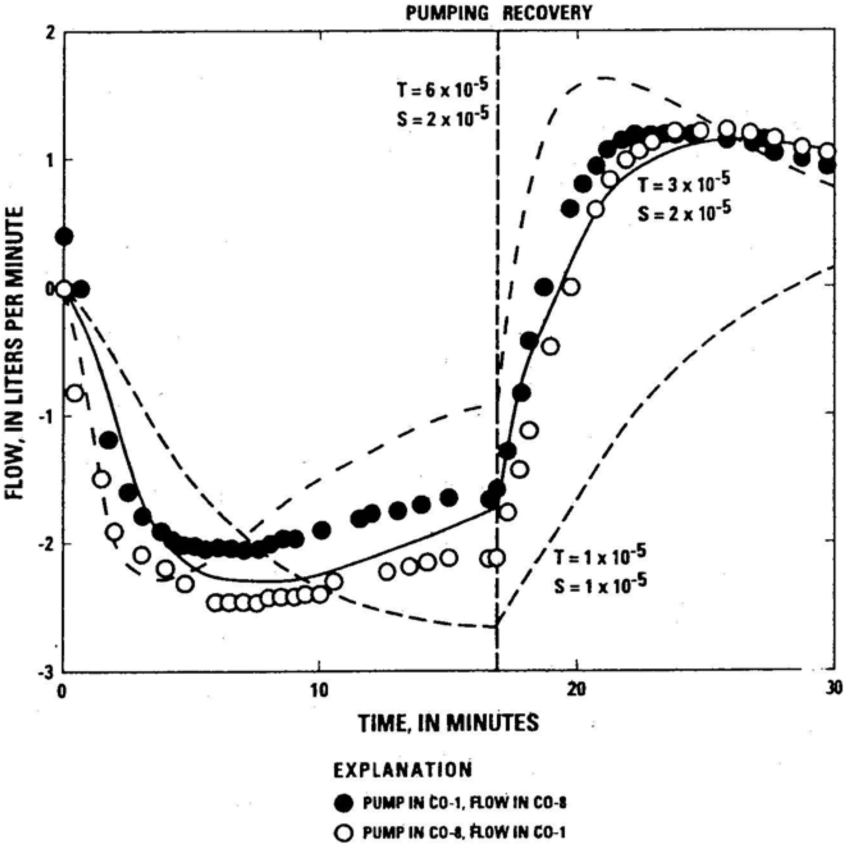

Figure 4 – Example of cross-borehole flowmeter experiments where flow response fits a model computed for a single horizontal fracture connecting the pumped and measurement borehole (from Paillet, 1998).

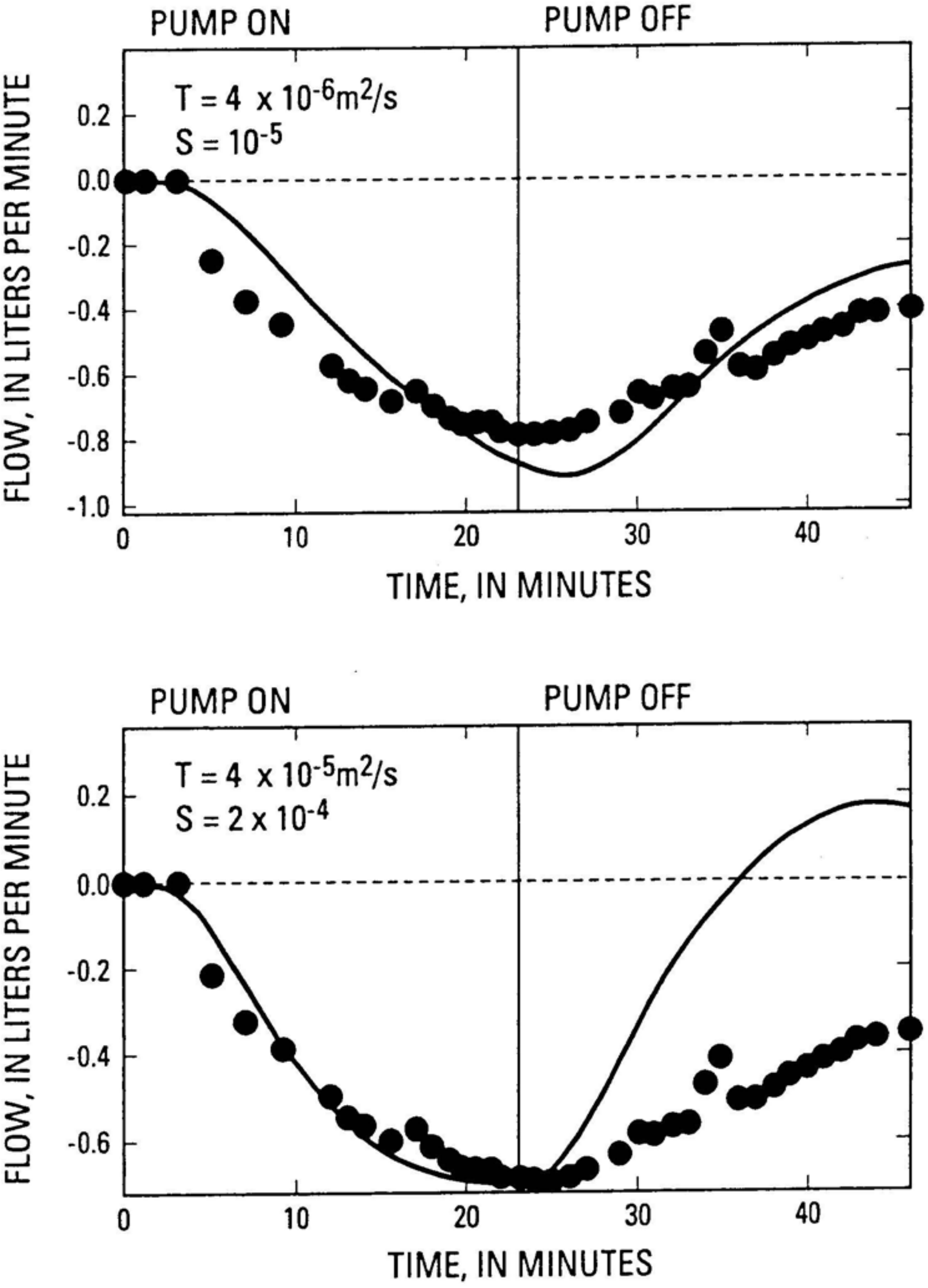

Figure 5 – Example of cross-borehole flowmeter experiment where geophysical logs indicate a single horizontal fracture projecting between boreholes, but where the asymmetry of the flow response indicates the fracture cannot be modeled as a laterally continuous feature of uniform transmissivity (from Paillet and Hanscom, 2000).

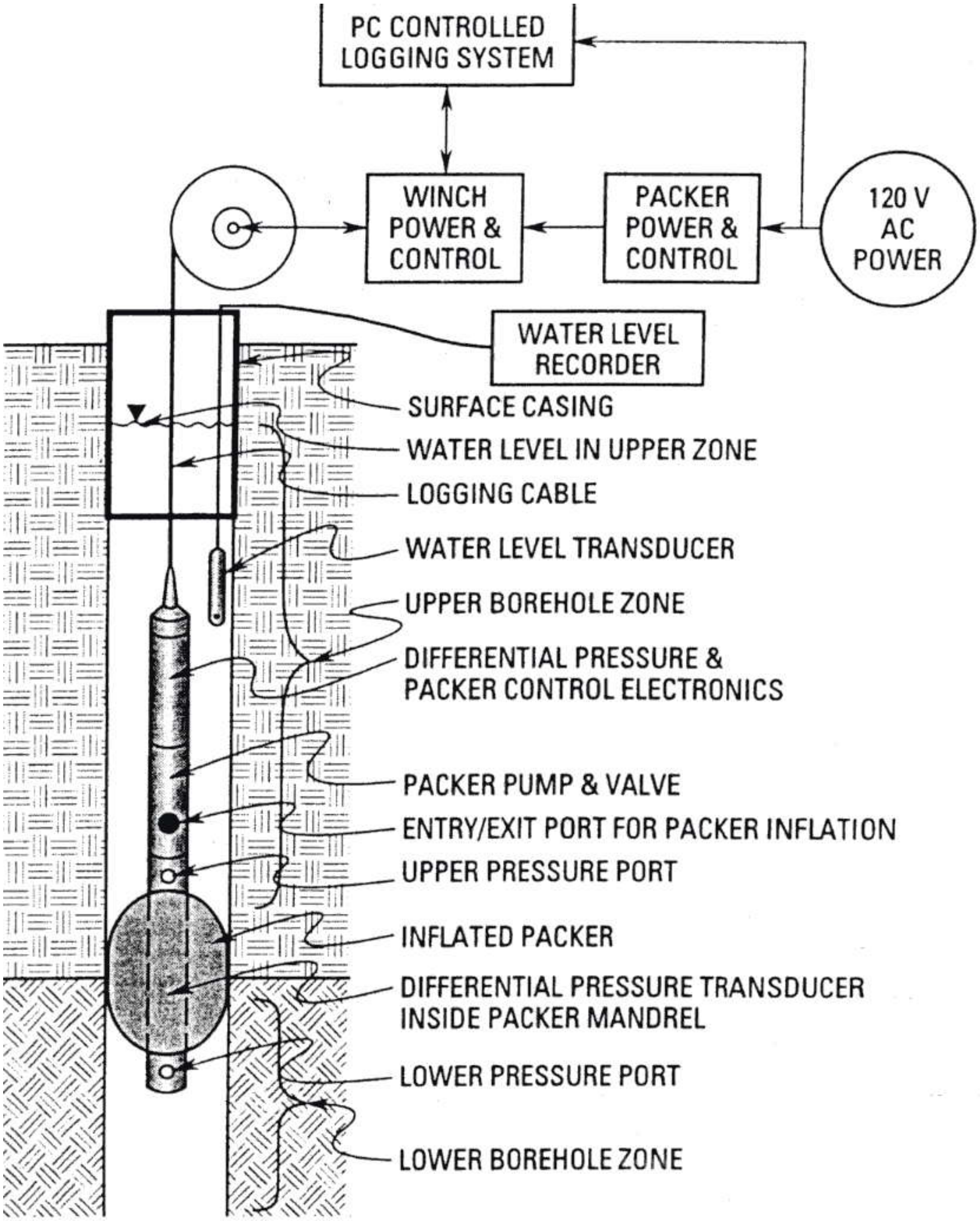

Figure 6 – Schematic illustration of borehole wireline-operated packer (from Paillet et al, 1998).

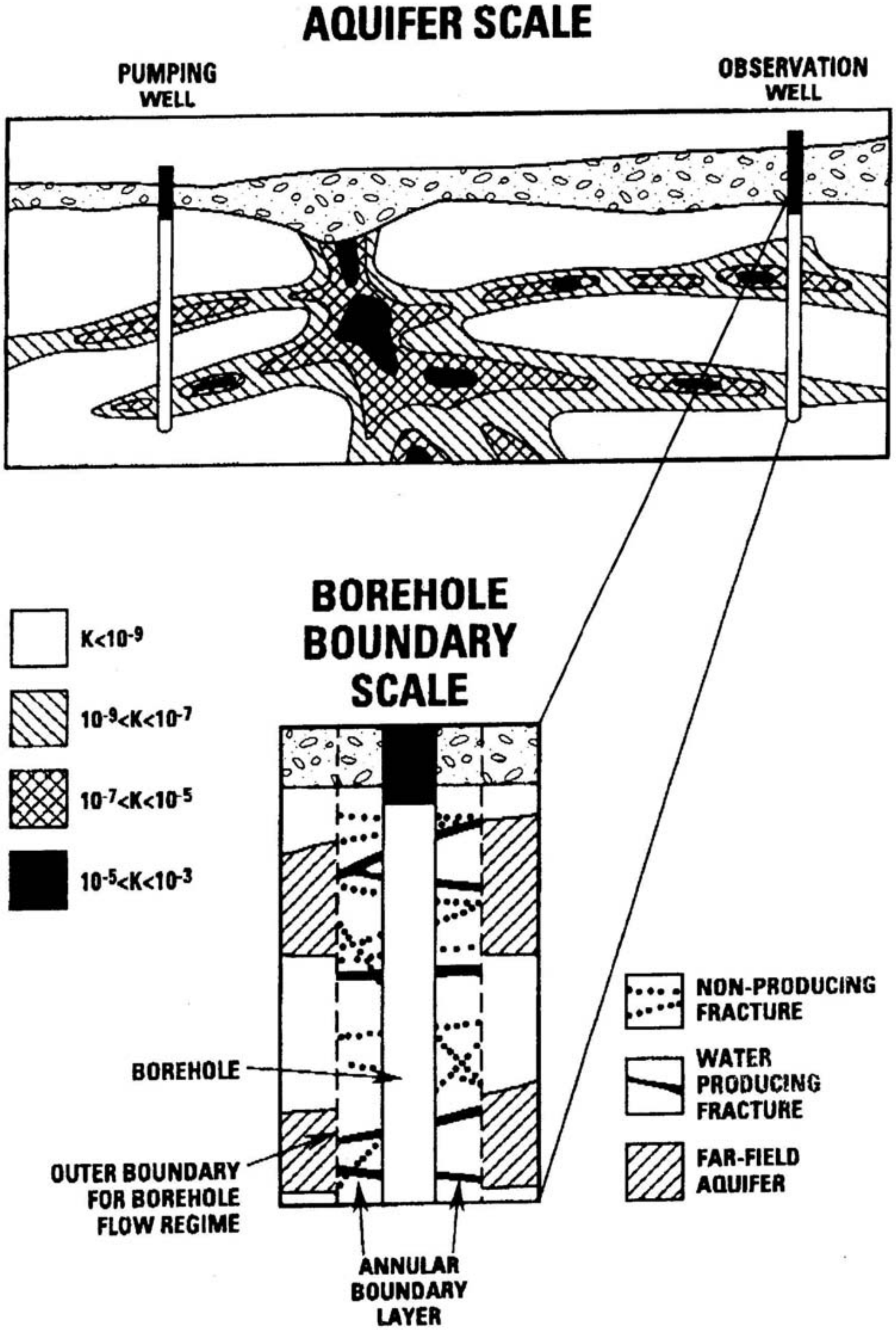

Figure 7 – Schematic illustration of borehole boundary region and the relationship between the outer boundary conditions for water producing-fractures in the borehole and the large-scale properties of the surrounding aquifer or aquifers.