IDENTIFICATION OF HYDRAULICALLY CONDUCTIVE FRACTURES INTERSECTING BOREHOLES IN FRACTURED GNEISS NEAR ASHFORD, CONNECTICUT

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CONVERSION FACTORS

Multiply	By	To Obtain
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06308	liter per second
meter	39.37	inch
centimeter	.3937	inch

The following terms and abbreviations also are used in this report:

microgram per liter (μg/L)
revolutions per second (r/s)
megahertz (MHz)

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ABSTRACT

A suite of geophysical logs designed to characterize fractures and water production from fractures was run in five boreholes ranging from less than 100 feet to more than 300 feet in depth in the vicinity of a suspected gasoline contamination site near Ashford in northeastern Connecticut. The geophysical logs used in this study are: conventional caliper log; borehole televiewer log, which produces a photograph-like image of the borehole wall; and the heat-pulse flowmeter, which produces a high-resolution profile of vertical flow in the well bore under ambient conditions and during injection. Downward flow was measured in three of the five boreholes under ambient conditions, while no flow was measured in one of the boreholes; a very weak upward flow in another borehole was attributed to recovery from pump removal. Steady injection tests at about 1.0 gallon per minute indicated that a limited number of the fractures intersecting the boreholes are capable of accepting water under injection conditions or of producing water under pumping conditions. Of the eight producing fractures identified on the televiewer logs in these boreholes, five appear approximately parallel in orientation to the NE strike and 30-degree NW dip of foliation bedrock; two others appear as steeply dipping fractures cutting across the foliation, and the other could possibly be assigned to either of these classes. Two other zones accept flow during injection tests, but are so close to the bottom of the borehole that they could not be characterized with geophysical logs. Although the data given in this report apply to only five boreholes, the orientation of producing fractures indicates that most of these fractures are parallel to NE strike and NW dip of both foliation and a regional thrust fault, and this orientation is consistent with downgradient migration of contaminants from a possible point source in the study area.

INTRODUCTION

Predicting the transport of contaminants in fractured rock bodies is one of the most difficult problems in hydrogeology. Much of this difficulty is a consequence of the heterogeneity of fractured rocks. For example, the distribution of fracture permeability may vary in a random way in all directions, making it nearly impossible to specify the transmissivity values to be used in a transport model. Borehole geophysical methods (well logs) are one of the most useful means for determining fracture permeability in boreholes. The geophysical study described in this report was undertaken as part of a U.S. Geological Survey program to develop well-logging techniques for the characterization of the hydraulic properties of fractured rocks. The Ashford study provided access to boreholes and was conducted in cooperation with the State of Connecticut Department of Environmental Protection (DEP) and the Department of Geology and Geophysics at the University of Connecticut (UConn). This site provided ideal conditions for testing well-logging equipment and well-log analysis techniques. The Ashford site is being studied to understand how fractures contribute to the dispersal of hydrocarbon contamination of ground water at this site.

In July 1987, an octane-enhancing gasoline additive, methyl tertiary-butyl ether (MTBE) was detected in a residential bedrock well at a concentration 29 times greater than the State of Connecticut drinking water standard of 100 µg/L. Since then, MTBE has been detected in 10 additional bedrock wells in the area. In 1988 and 1989, soil and ground-water investigations were conducted by two environmental consulting firms at two nearby gasoline stations (boreholes XM and CI in fig. 1). In October 1990, a community water supply was installed that allowed researchers access to temporarily abandoned residential wells for geophysical, hydraulic, and chemical testing.

As part of the investigation of bedrock well contamination, the Connecticut DEP has begun a study of the Ashford bedrock aquifer, which includes the use of borehole geophysical techniques described in this report. Although results are still being compiled, it is possible that the delineation of a contaminant plume may be used to infer large-scale hydraulic properties of the Ashford aquifer.

Purpose and Scope

This report presents the geophysical well-log data obtained at the Ashford, Connecticut, site in a format designed to be accessible to hydrogeologists interested in fracture hydrology and specification of parameters for contaminant transport models. These data include borehole wall images and caliper logs that indicate the distribution of fractures in five boreholes located along the axis of the distribution of contaminated wells. The data also include flowmeter profiles obtained under ambient conditions and during injection tests. The flowmeter log data may be used to infer the location of fractures capable of producing water during pumping, indicating those fractures possibly connected to larger-scale flow systems. The data provide useful information about the fractures encountered in the five Ashford boreholes, and about the subset of those fractures associated with hydraulic transport during pumping. This report is written to make that data available to U.S. Geological Survey and State of Connecticut scientists engaged in the long-term study of the Ashford, Connecticut, fractured rock aquifer.

Acknowledgment

This research is funded in part through a cooperative agreement grant No. CR-817587-01 with the Environmental Monitoring Systems Laboratory, Las Vegas, Nevada, U.S. Environmental Protection Agency. This paper has not been subject to official Agency review and no endorsement should be inferred. Mention of trade names herein does not infer endorsement of any kind.

SITE LOCATION AND GEOLOGICAL BACKGROUND

The study site is located in the town of Ashford in northeastern Connecticut (fig. 1). A total of 16 boreholes (bedrock water supply wells) are located along U.S. Highway 44 in a profile extending about 2,000 ft southwest from the U.S. Highway 44/State Highway 74 intersection. The developed parts of the site consist of 4 businesses and 12 residences. The undeveloped areas are wooded hillslopes and stream valleys, and a small area of pasture. The U.S. 44/State 74 intersection may be the approximate

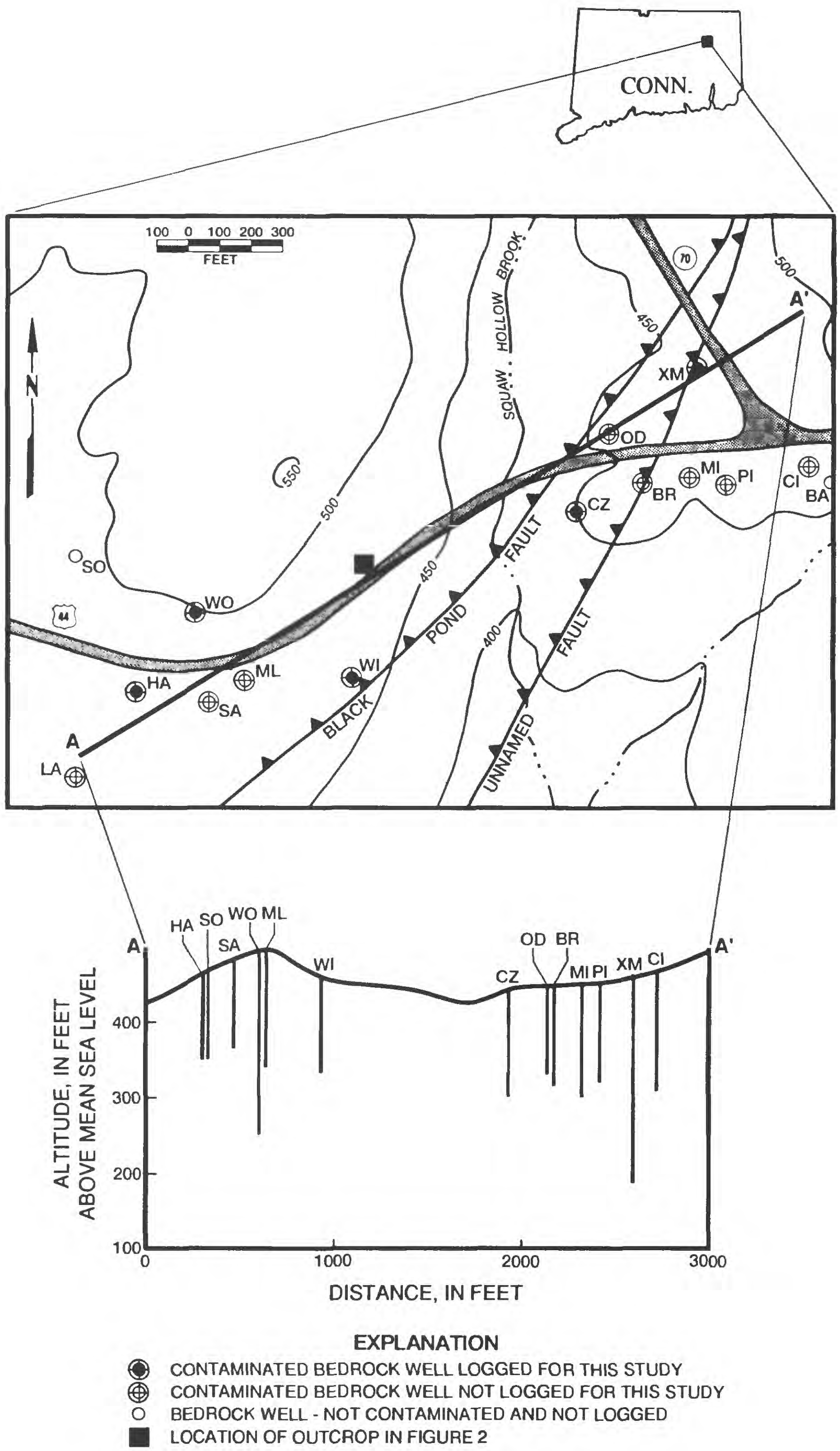

Figure 1. Location of boreholes at the Ashford, Connecticut, study site.

location where an underground storage tank was the source of the hydrocarbon contamination identified in local water wells, including the five boreholes logged during this study. Another potential source is near borehole HA (fig. 1), the site of a former underground gasoline storage tank.

Squaw Hollow Brook flows south through the site bisecting it into two parts. The eastern part of the site consists of level to moderately sloping ground where two of the logged boreholes, XM and CZ are located. The remaining three boreholes, WO, WI, and HA are west of Squaw Hollow Brook on the southern slope of a hill.

Soils at the site consist of fine sandy loam and silt loam that have formed from till (U.S. Department of Agriculture, 1981). The till, deposited during the Pleistocene glaciation, averages about 15 ft thick at the site. It consists primarily of an oxidized, olive-brown, very compact lower till that, in places, may be overlain by a less oxidized, olive-gray, very friable upper till (Rahn, 1968). Soil borings obtained in the vicinity of borehole XM indicate that the till ranges from 10 to 24 ft thick. Several borings contained as much as 7.5 ft of saprolite (IEP, 1989). This material, uncommon in the glaciated northeastern United States, consists of dense, fine to medium brown sand that contains fines and some angular rock fragments. Considering the locations of the soil borings in relation to bedrock faults and topography, this material may be related to fault traces that pass through the area (fig. 1). Artificial fill (mostly near the U.S. 44/State 74 intersection and at the U.S. 44/Squaw Hollow Brook crossing) and rock outcrops compose the remainder of the surface cover.

Bedrock in the vicinity of the study site consists of two regionally metamorphosed formations (Pease, 1988). From east to west they are: (1) the upper member of the Southbridge Formation of the Paxton Group (Late Proterozoic in age); and (2) the Bigelow Brook Formation of the Brimfield Group (Cambrian in age). The Black Pond Fault defines the contact between the two formations (fig. 1).

The upper member of the Southbridge Formation generally consists of gray, weathering to brownish gray or olive, thinly layered, granular schist and gneiss. The dominant minerals are quartz, plagioclase, and biotite. Other interlayered minerals include muscovite, actinolite, diopside, and epidote (Pease, 1988). Orientation of foliation measured at nearby outcrops strikes Northeast and dips from 14 to 35 degrees Northwest.

The Bigelow Brook Formation is described as the lowest unit of a thick sequence of metasedimentary and metavolcanic rocks. The sequence is composed of gray, weathered to brownish gray, gneiss and schist. Quartz, feldspar, and biotite are the primary minerals; sillimanite, garnet, and sulfide minerals also occur. Surface outcrops have a pronounced layered appearance (fig. 2), and the rock layers produced by weathering along foliation planes dip from 20 to 55 degrees toward the west-northwest (Pease, 1988). These orientations are mapped by Pease as parallel to original layering and bedding.

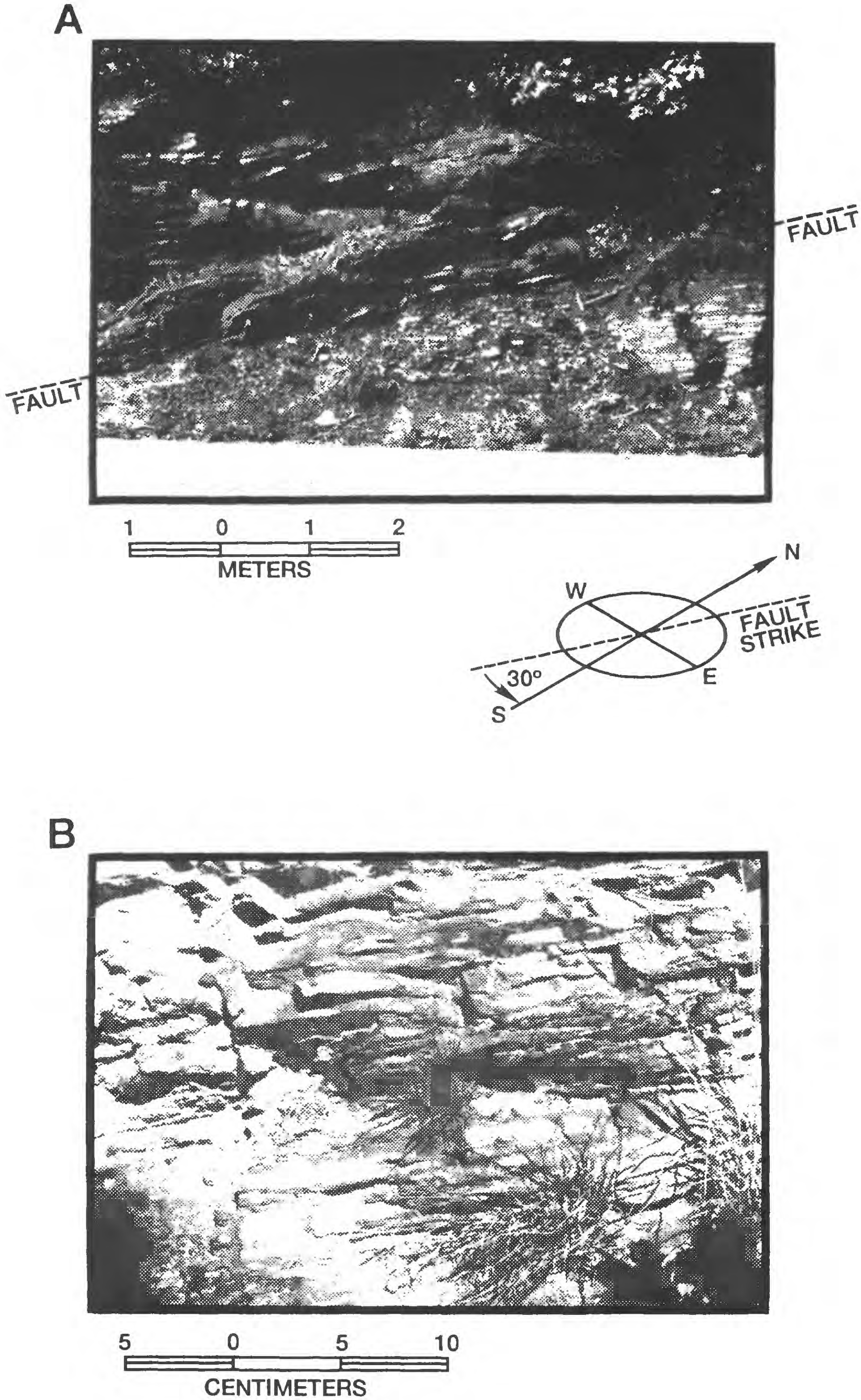

Figure 2. Photographs of outcrop adjacent to borehole WI illustrating: (A) orientation of fault exposed in outcrop along U.S. Highway 44; and (B) foliation planes and texture of the fractured rock aquifer at the Ashford, Connecticut, study site.

The Black Pond Fault and an unnamed fault trend north-northeast through the site and intersect each other north of the U.S. 44/State 74 intersection (fig. 1; Pease, 1988). They are late syntectonic, ductile, low-angle faults whose trends are roughly parallel to regional layering and foliation in high stress areas. The deformation probably started at amphibiolite-grade (ductile) metamorphism and continued to lower (brittle) grade. Many small structures such as folds and faults are in outcrops, although structural correlations between outcrops are poor (Pease, 1988). A fault that crops out along U.S. 44 was investigated as part of this study (fig. 2A). It strikes north-northeast and dips 54 degrees west-northwest. This strike is parallel to and the dip is slightly greater than that of regional faulting and foliation. Slickensides trending north-northwest on one of the exposed faces provide evidence of movement along the fault in that direction. From bedrock altitudes encountered in previous soil borings at the XM site, the local bedrock surface was contoured and shows a linear depression trending northeast (IEP, 1988). This linear depression may be the near-surface manifestation of the Black Pond Fault or the unnamed fault.

The site is in the Squaw Hollow Brook drainage basin, which is within the Natchaug regional basin. Local drainage is toward Squaw Hollow Brook, an intermittent stream south of U.S. 44, and Knowlton Brook (fig. 1).

Each of the businesses and residences at the site has at least one 6-in-diameter, drilled bedrock well ranging from less than 100 ft to about 300 ft in depth. Residence WO has an additional shallow dug well. Presently, four bedrock wells are pumped on a regular basis. They are wells BA (for washing), SA (for animals), and SO (for domestic supply) (fig. 1). The remaining wells are no longer pumped. A total of 14 surficial and 8 shallow bedrock monitoring wells have been installed by consulting firms at the 2 gas stations.

Two ground-water flow regimes are recognized; flow in the unconsolidated surficial deposits and flow in the bedrock. The surficial aquifer exists in a semi-perched state and can recharge the bedrock aquifer. In late August/early September 1991, the water table at the borehole WO site, as determined from the shallow well, was 53 ft higher than the water level in the bedrock well. Monitoring wells at the two gasoline stations (wells XM and CI) indicate that shallow ground-water flow near the U.S. 44/State 74 intersection generally is toward the south-southwest. Depths to ground water in the unconsolidatd deposits range from 4.4 to 18.8 ft below land surface (IEP, 1989). Measurements of water levels in the unconsolidated surficial deposits and bedrock aquifers show fluctuations in response to short-term storms and long-term seasonal effects. Horizontal hydraulic gradients in bedrock wells at the XM site range from 0.045 to 0.050. Vertical hydraulic gradients in the unconsolidated surficial deposits and shallow bedrock, as determined from well nests, were downward at 0.008 and 0.050, respectively (IEP, 1988).

GEOPHYSICAL EQUIPMENT AND HYDRAULIC TEST PROCEDURES

Five of the boreholes at the Ashford site (fig. 1) were logged with a conventional three-arm caliper logging system, the acoustic borehole televiewer, and a recently developed, high-resolution borehole flowmeter (boreholes HA, WO, WI, CZ and XM). These three logging methods were selected to identify the depths, orientation, and relative sizes of fractures intersecting the boreholes. In addition, the flowmeter measurements were used to identify entrance and exit points for flow under ambient conditions, and during borehole injection tests. These measurements were made to identify fractures that are capable of producing flow and therefore are connected to larger-scale bedrock flow systems.

Conventional Three-Arm Caliper Log

The conventional caliper log measures average borehole diameter by recording the average of the extension of three spring-loaded arms. The arms are about 0.25 in. in diameter and 6.0 in. in length. The borehole sonde is designed so that the resistance of sonde circuitry varies almost linearly with the average extension of the caliper arms. Caliper logs indicate the abrupt, local borehole enlargements where fractures intersect the borehole, so the caliper log can be a useful fracture indicator (Keys, 1979, 1991). However, the natural aperture of individual fractures is almost always less than the diameter of the caliper arms, so the tips of the caliper arms cannot fit into such openings. Therefore, the borehole enlargements sensed by caliper logs usually represent enlargements of the borehole-fracture intersection produced by spalling during drilling or by erosion of soft alteration products and fracture infilling clays. For this reason, anomalies on caliper logs are used as indirect indicators of fracturing (Keys, 1979).

Acoustic Borehole Televiewer (BHTV) Log

The BHTV log produces a photographic image of the borehole wall that indicates the intensity of acoustic reflections from a source scanning the borehole wall at about 3 r/s (Zemanek and others, 1970; Paillet and others, 1990). The source transducer uses a 1.25 MHz signal and has a beam width of about 0.3 in. At those depths where fractures intersect the borehole wall, the intersection scatters acoustic energy, which produces a linear feature on the photographic output from the BHTV (fig. 3). The orientation of these features can be used to infer strike and dip of fractures with respect to the borehole axis. The azimuthal orientation of the televiewer image is determined by the local direction of magnetic north. Laboratory calibrations and other equipment checks indicate that the BHTV horizontal sweeps are triggered within a few degrees of the component of the earth's magnetic field in the plane transverse to the borehole axis. Unless boreholes are deviated more than 40 degrees from the vertical at sites in southern New England, we estimate that all azimuths given on BHTV logs have an error of less than $\pm$ 5 degrees. This estimated error represents more than two standard deviations as determined from laboratory calibration data. In borehole WO, local concentrations of magnetite disrupted the orientation of borehole images over several short intervals, each of which were no more than a few feet in length. In these limited situations, the BHTV logs were rerun using an internal "mark" to trigger scanning sweeps on the oscilloscope display. This process produces unorientated images, which then were related in short

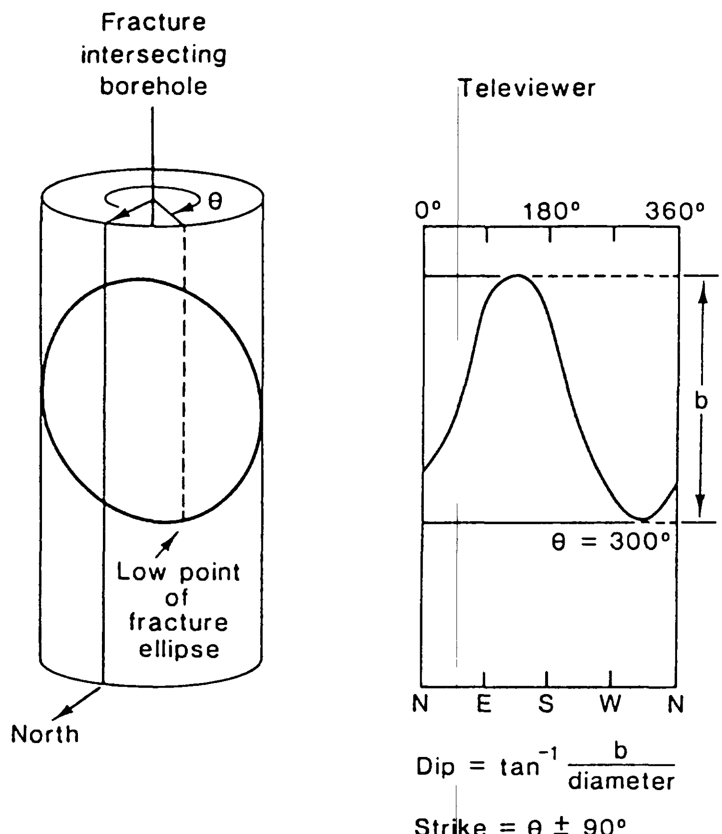

Figure 3. Schematic illustration of fracture on borehole televiewer log, indicating interpretation of fracture strike and dip from the photographic display produced by the borehole televiewer output.

intervals of overlap to the orientated images from unaffected intervals above and below. In these few situations, the azimuths given on the BHTV images are estimated to have an error of up to ± 10 degrees.

The azimuth triggering mechanism of the BHTV logging system determines orientation of BHTV image logs, but is not the only factor that determines the error in estimating of the strike and dip of fractures identified on logs. Errors in the interpretation of fracture strike and dip can result from departures of the fracture image from the expected shape indicted in figure 3. Whenever fractures have the expected shape as predicted for the intersection of a planar feature with a cylindrical borehole, fracture strike and dip can be estimated to within an error of ± 10 degrees. The vertical scale of image logs also determines the ability to discriminate between shallow-dipping and horizontal fractures. When a vertical scale of 2 ft. per in. is used, experience indicates that a fracture needs to be dipping at greater than 15 degrees from horizontal before the dip can be identified on the BHTV log images.

BHTV logs provide a qualitative indication of fracture size because fractures with larger apertures appear as wider, darker features on the BHTV display. The width of the linear feature associated with a fracture can be inferred from the scale of the photographic output of the logging system, but the width of these lines represents fracture aperture at the borehole wall convolved with the 0.3-in.-wide source beam. It also is probable that the fracture width at the borehole wall has been enlarged during drilling, so an aperture measured there would not be representative of the fracture aperture in the undamaged formation. Specific examples of the interpretation of fracture aperture using BHTV logs are given by Keys (1979), Paillet and others (1985), and Paillet (1991).

Heat-Pulse Flowmeter (HPFM) Log

The HPFM was developed to provide a borehole flowmeter with greater sensitivity than conventional impeller flowmeters, which require axial flow velocities larger than several feet per minute to turn the impeller blades (Keys, 1991). The HPFM measures axial flows along the borehole at discrete depths by detecting the time required for a small volume of thermally tagged water to travel from the heat grid to a thermistor in the measurement section of the tool (Hess, 1986) (fig. 4). The sensitivity of the HPFM is increased by the use of a downhole packer system that uses an inflatable bladder to block the annulus around the tool, which forces all flow through the measurement section. With the packer inflated, the inverse of heat-pulse travel time is calibrated in terms of borehole discharge in gallons per minute. Experiments at the U.S. Geological Survey flowmeter calibration facility demonstrate that the HPFM can detect flows as small as 0.01 gal/min (Hess and Paillet, 1990).

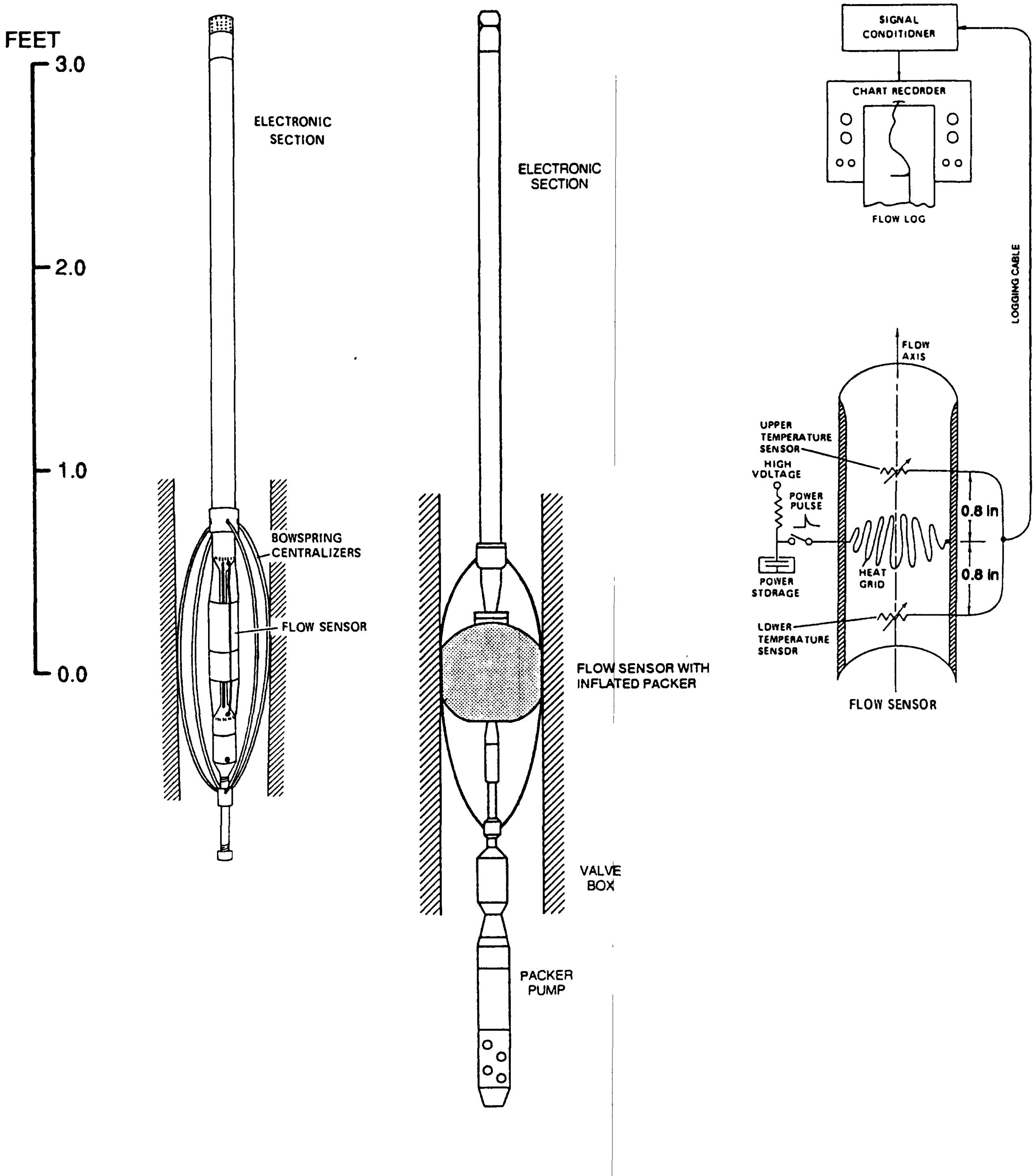

Figure 4. The U.S. Geological Survey heat-pulse flowmeter, illustrating configuration of heat grid and thermistors in the measurement section, and configuration of flow-concentrating downhole packer.

Flowmeter Logging During Injection Tests

On the basis of experience at several different fractured rock study sites (Paillet, 1991) the U.S. Geological Survey has developed a standardized procedure for using HPFM measurements during pumping or injection to identify productive fractures (Paillet and others, 1987). During the injection procedure, the HPFM is lowered into the borehole and a large number of measurements are made at various depth stations to determine whether there is flow along the borehole driven by ambient hydraulic head differences between fractures before injection is started. If such ambient flow exists, HPFM measurements are made to identify the depths where flows enter and exit from the borehole.

Additional HPFM measurements are begun from 15 minutes to an hour after injection is started and maintained at a nearly steady rate of about 1.0 gal/min. For the Ashford measurements, injection was accomplished by means of a hose connected to a municipal water supply system. Water-level measurements are made at regular intervals during pumping, if possible. HPFM measurements are made during the injection at discrete stations between depths where fractures intersect the borehole.

HPFM measurements made during the injection test need to be adjusted to correct for variation in the proportion of the constant injection rate that contributes to storage in the well bore (Paillet and Kapucu, 1989). The proportion of injected water that goes into well-bore storage generally decreases with time as flow into the formation increases. Therefore, the magnitude of flow in the well bore below casing changes in the time during the experiment, and HPFM data need to be normalized to correspond to recharge conditions at a given time. It is assumed that the increase in water level in casing is proportional to the total rate of flow to the formation, and estimates of water level increase can be used to normalize the data. HPFM measurement normalization is accomplished by fitting the measured water-level build-up over time to a smooth exponential curve. The fraction of injected water accepted by the formation is assumed to be proportional to the increase in water level at any given time. If conditions preclude direct measurement of water levels in the pumped borehole, formation recharge is estimated by taking repeat HPFM measurements at a reference location in casing. These measurements can be fitted to an exponential curve in a manner analogous to the use of build-up data, and the same normalization procedure is applied to the data.

After the HPFM measurements of borehole flow are tabulated and normalized according to the exact time of measurement, the HPFM data are used to construct a vertical flow profile for the borehole during pumping or injection. This profile indicates the depths where producing fractures intersect the borehole. In this study, fractures accepting flow during recharge are assumed to produce flow during pumping. Comparison of the flow profiles with the fracture locations given by the caliper and BHTV logs often permits the inflow or outflow to be associated with a single fracture.

FRACTURES AND PRODUCING INTERVALS IN THE ASHFORD BOREHOLES

BHTV and caliper logs were run in five boreholes indicated in figure 1 during August 7-9, 1991 (boreholes HA, WO, WI, CZ, and XM). Flow under ambient conditions occurred in three of the five boreholes (boreholes WO, WI and CZ), and drawdown by a local water supply well was affecting at least one of the boreholes (borehole CZ) during the measurement period. The results of the caliper, BHTV, and HPFM measurements in the five boreholes are illustrated in figures 5-9.

Borehole HA

The BHTV and caliper logs for borehole HA (fig. 5) indicate six or more fracture zones intersecting the borehole. Most of these are in the form of openings that appear parallel to the NW dipping and NE striking foliation planes. This secondary permeability could be either fractures or openings produced by weathering along foliation planes.

Naturally occurring flow under ambient hydraulic-head conditions was not detected in borehole HA. HPFM measurements during injection indicated the same constant downward flow over the entire length of the borehole. Within the resolution of the HPFM, only a single fracture located within 2 ft of the bottom of the borehole is both transmissive and connected to other fractures and thus is capable of accepting flow during the injection experiment. This fracture intersects borehole HA in the "blind spot" below BHTV coverage where the lower tool centralizer and base of the electronic section prevents the transducer from scanning the borehole wall. For this reason there is no BHTV image available for the producing fracture in borehole HA.

Borehole WO

The BHTV and caliper logs for borehole WO (fig. 6) indicate that numerous fractures and openings parallel to foliation intersect the well bore, but only the major fracture near 95 ft in depth is associated with a large caliper anomaly. Most but not all of these openings or possible fractures are nearly horizontal or dip NW and strike NE at angles similar to the strike and dip of foliation.

Ambient flow was measured at about 0.1 gal/min downward, which entered the borehole from one of several minor features indicated on the BHTV log above 70 ft in depth, and exited below 230 ft. The depth interval on the BHTV log where the inflow occurs under ambient conditions does not show anything that appears like an open fracture on the BHTV image. However, there are a few faint features that appear identical to indications of foliation planes present in the BHTV log throughout most of the borehole.

The flow regime produced by the injection tests accentuated the natural downflow driven by ambient conditions. HPFM measurements indicated that most of this flow exited at a fracture at about 239 ft in depth. This fracture appears as a relatively large opening nearly parallel to NW dipping foliation. However, this feature is irregular enough that it could represent the intersection of a fracture cutting across foliation, where the intersection of the fracture with this borehole wall has been extensively damaged during drilling.

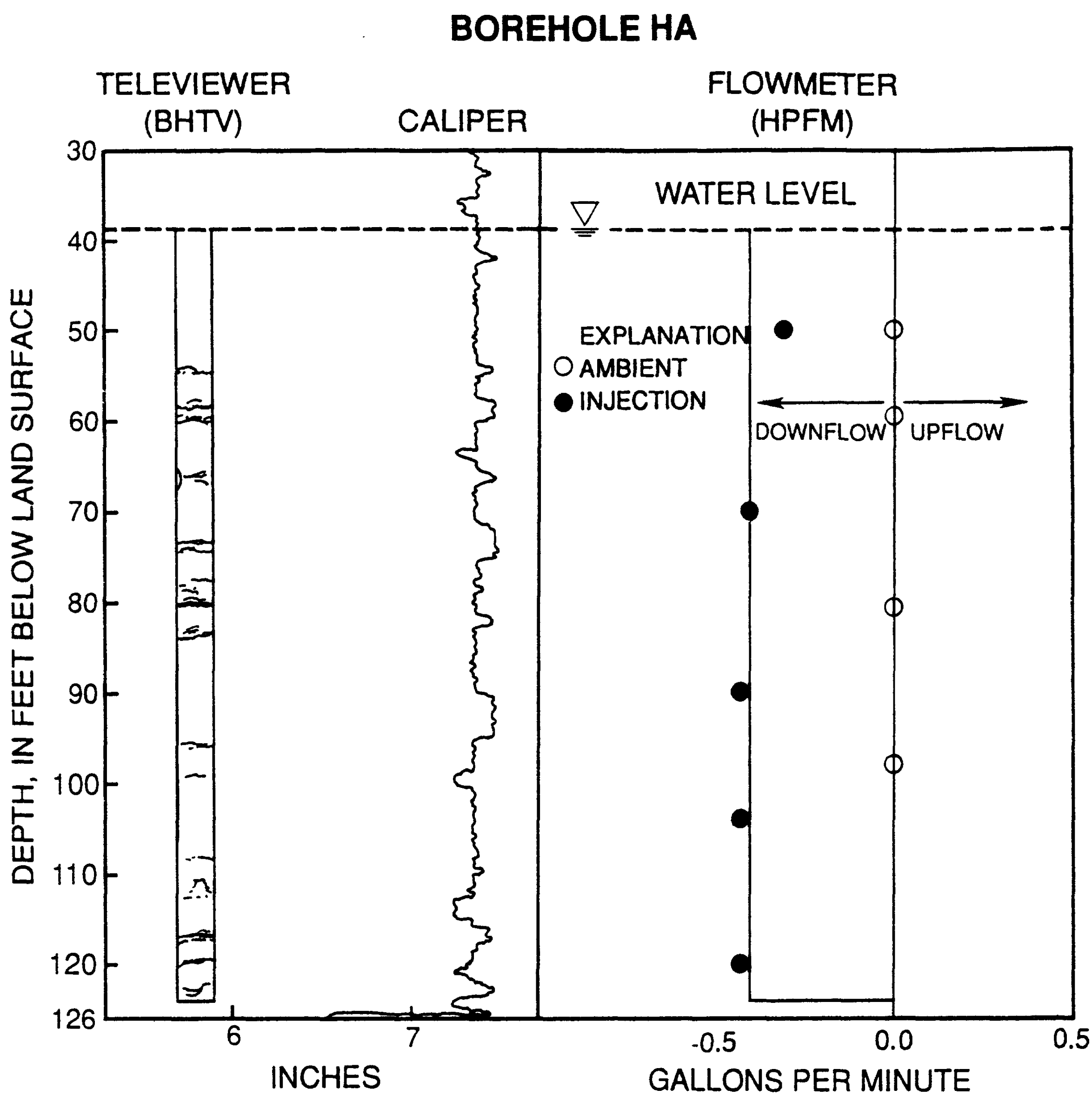

Figure 5. Borehole televiewer and caliper logs and heat-pulse flowmeter data obtained under ambient conditions and during recharge in borehole HA.

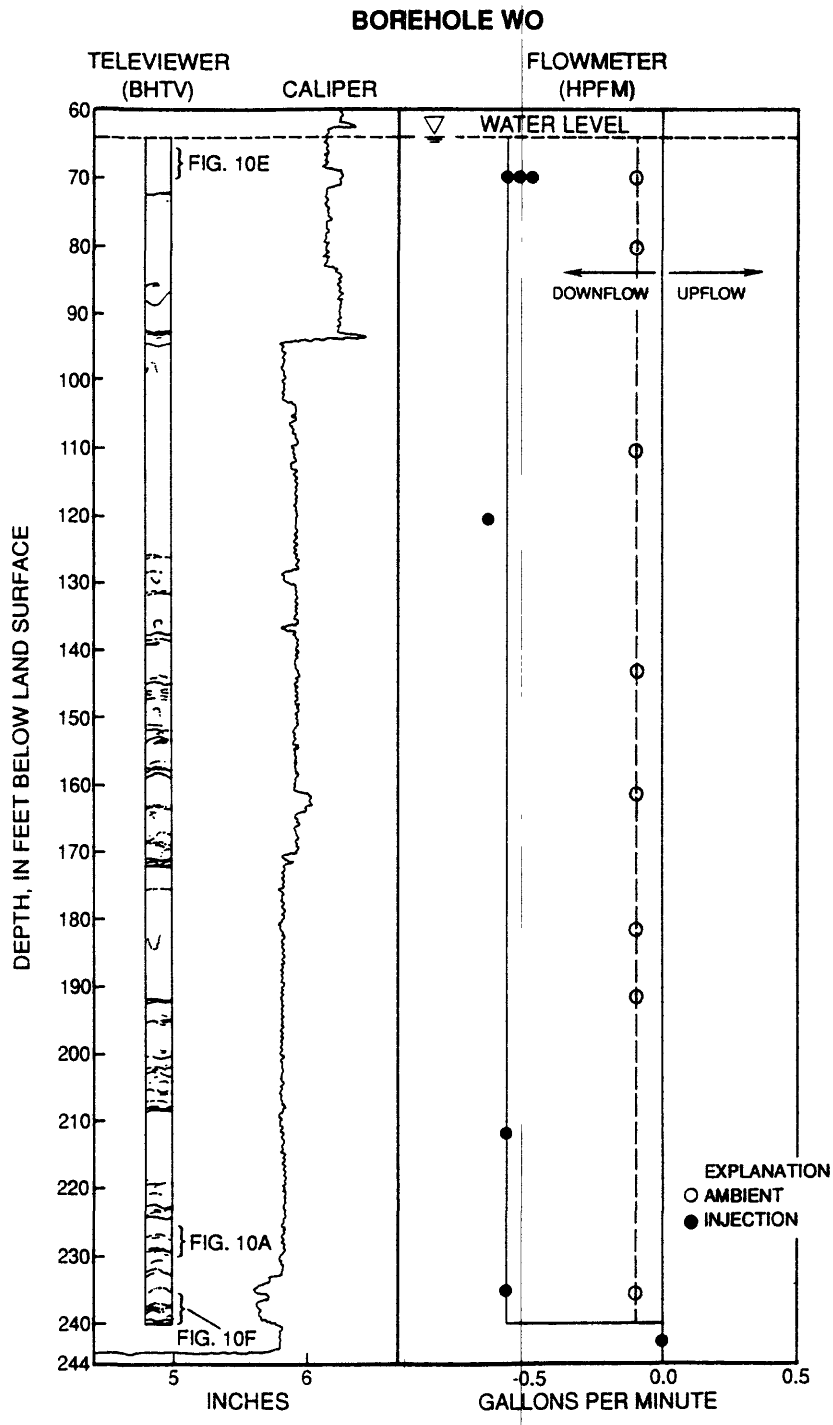

Figure 6. Borehole televiewer and caliper logs and heat-pulse flowmeter data obtained under ambient conditions and during recharge in borehole WO.

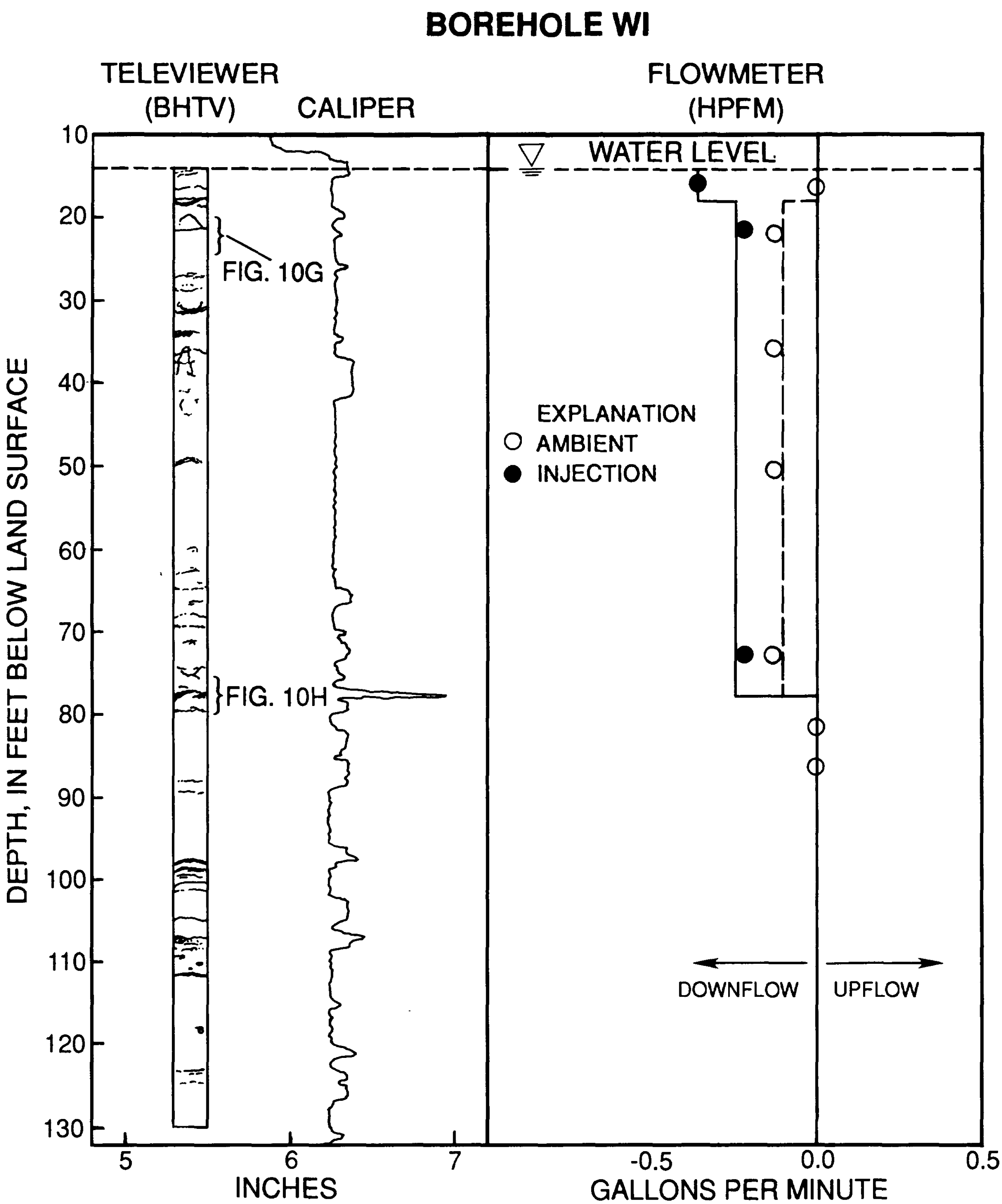

Figure 7. Borehole televiewer and caliper logs and heat-pulse flowmeter data obtained under ambient conditions and during recharge in borehole WI.

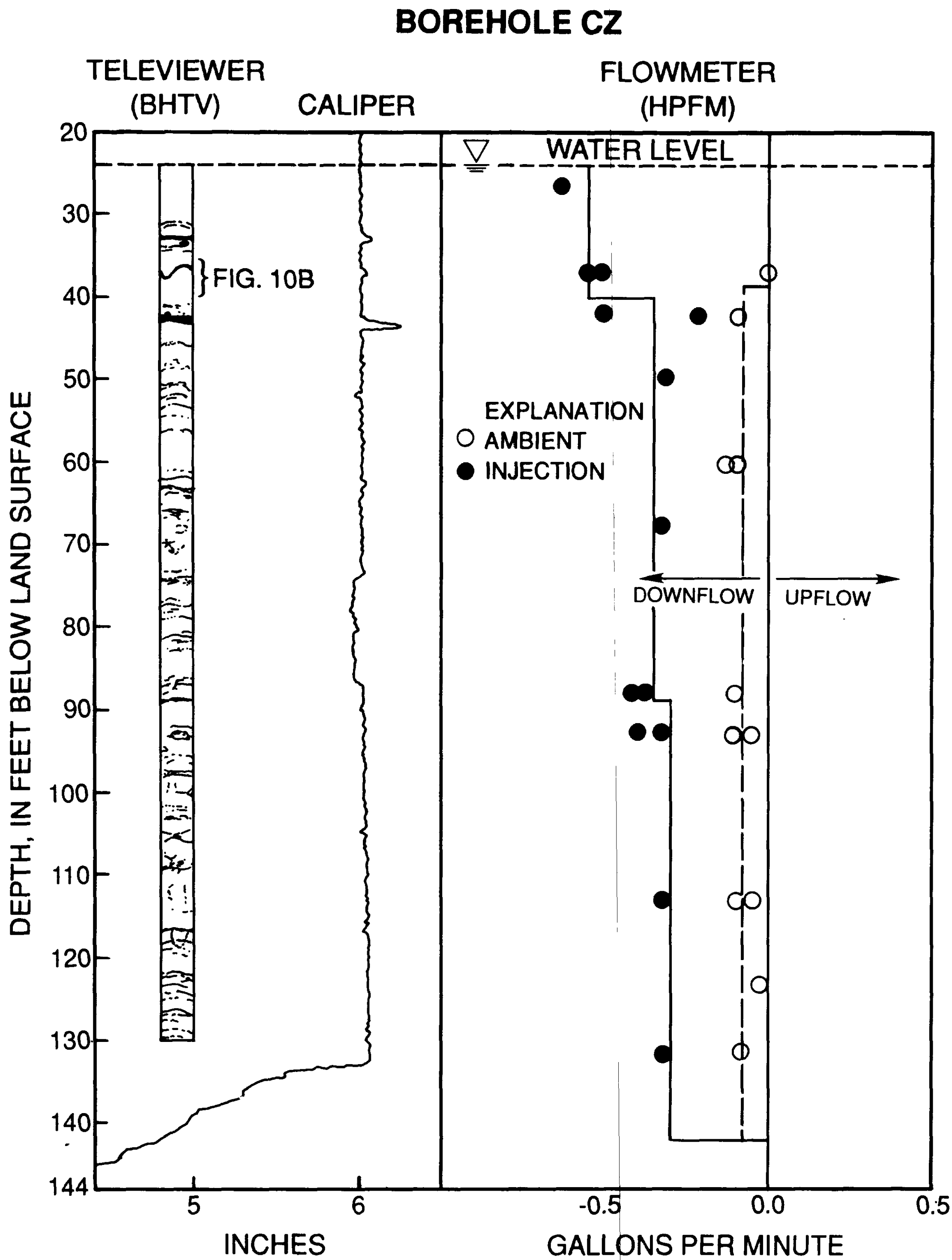

Figure 8. Borehole televiewer and caliper logs and heat-pulse flowmeter data obtained under ambient conditions and during recharge in borehole CZ.

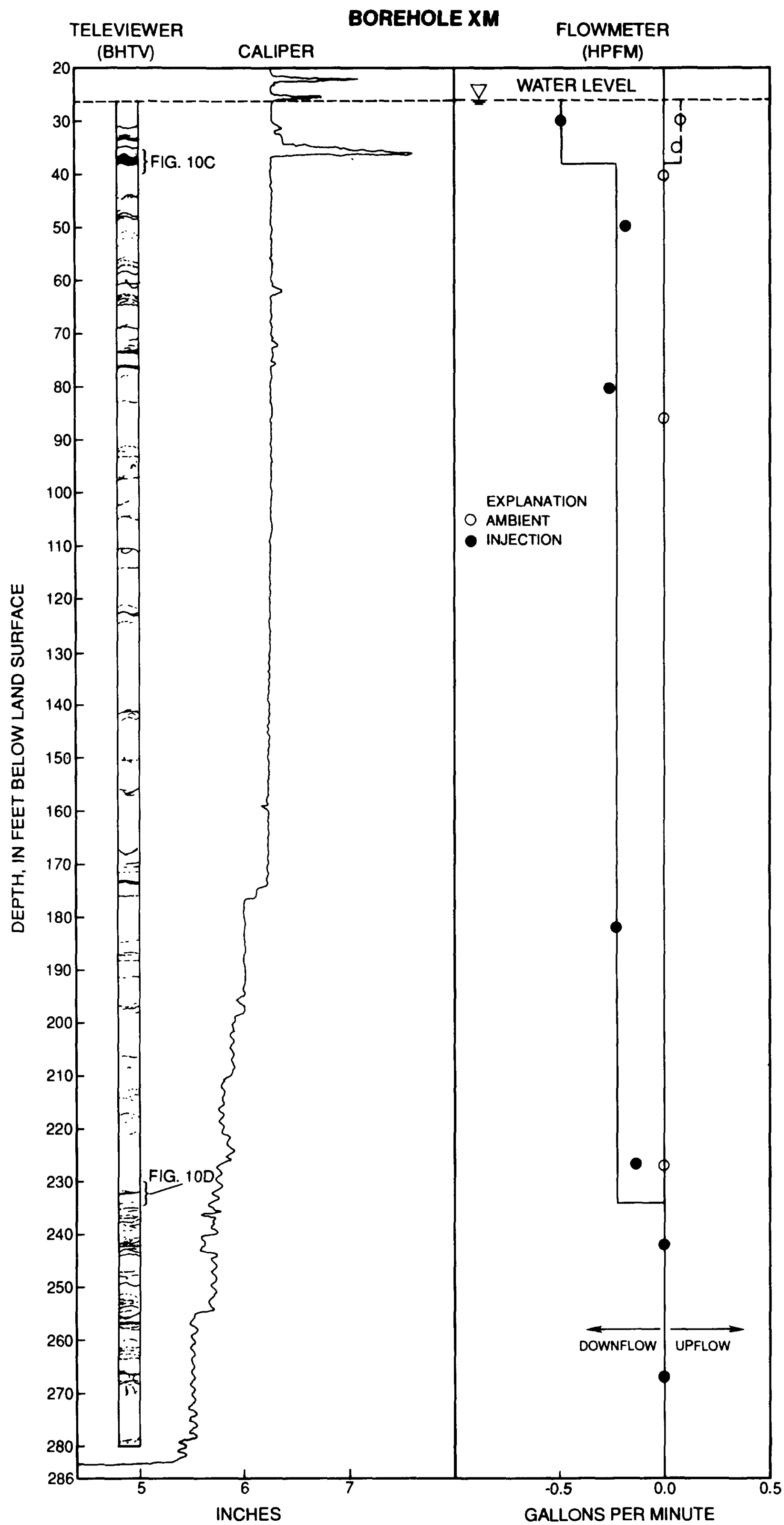

Figure 9. Borehole televiewer and caliper logs and heat-pulse flowmeter data obtained under ambient conditions and during recharge in borehole XM.

Borehole WI

The BHTV and caliper logs for borehole WI (fig. 7) indicate a number of fractures and openings parallel to foliation, including an especially large fracture near 78 ft. This large fracture is associated with a very large caliper anomaly. A prominent fracture that definitely cuts across foliation planes is evident on the BHTV log near 19 ft., but this fracture is not associated with a significant anomaly on the caliper log.

The HPFM measurements indicated flow under ambient conditions in borehole WI. The inflow and exit points for this flow definitely could be associated with features on the BHTV log; inflow occurred at the fracture near 19 ft, and outflow at the large opening near 78 ft.

The HPFM measurements during injection tests indicated that all downward flow exited at the two points involved in the entry and exit of the flow under ambient conditions. Although the increased flow rates under injection increased the resolution of the HPFM, no other fractures or openings along foliation planes were associated with outflow. The normalized outflow at the opening near 78 ft is two or three times greater than the outflow at the fracture near 19 ft in depth, and, therefore, the lower fracture is at least twice as transmissive as the upper fracture.

Borehole CZ

The BHTV and caliper logs for borehole CZ (fig. 8) indicate numerous possible openings parallel to foliation and three larger openings from 30 to 50 ft in depth. Two of these openings are either horizontal or parallel to foliation; the one near 43 ft in depth is associated with a large anomaly on the caliper log. The third opening near 37 ft in depth is clearly a steeply dipping fracture that cuts across foliation, striking NNW and dipping about 71 degrees to the ENE.

The HPFM measurements detected downflow under ambient conditions. The downflow entered at the steeply dipping fracture near 37 ft in depth, and exited at a depth below a constriction in the borehole that prevented televiewer logging below 130 ft in depth. The outflow was assumed to occur in the interval from 130 to 144 ft in depth. The HPFM data in figure 8 showed some scatter that seemed to indicate variation in flow during the measurement period rather than just experimental error, and irregular water level changes were measured in borehole CZ during the ambient flow measurements. This transient fluctuation in water level was probably caused by pumping from water supply wells in the vicinity of the study site.

The HPFM measurements during injection indicated outflow at the fracture near 37 ft in depth and below 130 ft in depth. In addition, a small volume of outflow was detected at a nearly horizontal feature indicated on the BHTV log near 88 ft in depth. Variations in the background flow regime indicated by variations in vertical flow measured under ambient conditions also seemed to affect the HPFM measurements during injection. The relative magnitudes of the outflow during the injection experiment indicate that the lowermost fracture zone (130-144 ft) is about twice as transmissive as the fracture near 37 ft, which, in turn, is about five times more transmissive than the feature near 88 ft.

Borehole XM

The BHTV and caliper logs for borehole XM (fig. 9) indicate a number of openings parallel to foliation and possible fractures. However, one unusually large fracture near 37 ft in depth is associated with a large caliper anomaly. This fracture has a relatively distinct lower edge on the BHTV log, which indicates NE strike and NW dip close to that of foliation. The vertical extent of the BHTV image indicates a width for this opening at the borehole wall of more than 2 ft. This feature seems much too large to be a natural fracture. The large apparent aperture given on the BHTV and caliper logs may have resulted from the erosion of altered rock adjacent to a fracture during drilling, or may indicate a pull-apart zone in a fault. Below about 200 ft in depth, the caliper log indicates a waviness in the borehole wall. This characteristic could be related to the texture of the rock, but it probably is an artifact of noise produced by the presence of a powerline adjacent to the site. If this feature is induced by cultured noise, the length of cable extending along the borehole could influence the strength of the signal from the powerline, accounting for the severity of the noise at depths below 200 ft.

The HPFM measurements made before the start of recharge in borehole XM indicated barely measurable upward flow under ambient conditions. However, water-level measurements indicated that the borehole was still recovering from the drawdown produced by the removal of a suspended pump about one hour earlier. The measured upflow at the time of logging is attributed to this recovery and is not interpreted as indicative of an ambient hydraulic-head difference between fractures intersected by borehole XM. The HPFM data indicated inflow at the large opening near 37 ft in depth and outflow to storage in casing.

The HPFM measurements made during injection in borehole XM indicated outflow at the large opening near 37 ft and at another large opening near 232 ft in depth. None of the other apparently large openings or fractures intersected by the borehole seemed to transmit flow, including the large openings parallel to foliation in the interval from 50 to 80 ft in depth. The relative volume of flow exiting at the two outflow points indicate that the opening near 37 ft in depth is about 1.5 times as transmissive as the opening near 232 ft in depth. However, the rate of rise of water level in borehole XM during recharge indicated that both of these openings are less transmissive than the most transmissive fractures encountered by some of the other boreholes. For example, the large opening in borehole XM near 37 ft in depth accepted about 0.2 gal/min of recharge under about the same recharge conditions at which the major fracture near 240 ft in depth in borehole WO was accepting about 0.6 gal/min. This result indicates that the transmissivity of the fracture at 37 ft in depth in borehole XM is no greater than that of other conductive fractures intersected by other boreholes, in spite of the very large local fracture aperture indicated on the caliper and BHTV logs.

FRACTURE FLOW PATHS IN THE ASHFORD BEDROCK AQUIFER

The geophysical well-log data obtained in the five boreholes shown in figure 1 provide a sampling of fractures in the bedrock aquifer that supplies domestic wells in Ashford, Connecticut. The BHTV and caliper log data indicate that each of these boreholes intersects a number of possibly transmissive features, many of which are parallel to the consistently NW dipping foliation planes. The foliation is indicated by poorly defined features on the BHTV log (fig. 10A). The approximately 30-degree NW dip of these features agrees with the strike and dip of foliation measured in outcrop near borehole WI (fig. 2). More than half of all features that are qualitatively interpreted as locally permeable according to the criteria given by Paillet and others (1985) seem to be parallel to foliation and may have originated by rock failure or weathering along foliation planes (table 1). The smaller number of fractures crossing foliation planes on the BHTV logs seem to display no consistent orientation.

Table 1--Summary of eight producing fractures identified with the acoustic televiewer log and inferred to be connected to larger scale fracture flow systems on the basis of the flowmeter measurements during injection tests; two other producing fractures could not be logged with the acoustic televiewer.

DESIGNATION IN FIG 10	BOREHOLE DESIGNATION	APPROX DEPTH (FEET)	STRIKE[1] (DEGREES)	DIP (DEGREES/DIRECTION)
B	CZ	37.5	116	71/NNE
not illustrated	CZ	89.0[4]	75[2]	22/NNW[2]
C	XM	36.5	17[2]	31/W[2]
D	XM	232.0	57[2]	22/NW[2]
E	WO	68.0	55[2]	22/NW[2]
F	WO	239.5	40[2]	22/NW[2]
G	WI	19.0	100	54/NNE
H	WI	77.0	?[3]	?[3]

[1]Corrected for magnetic declination.

[2]Character of fracture or opening indicates that this fracture is approximately parallel to foliation.

[3]Fracture or opening could be a fracture cutting across or parallel to foliation; either interpretation is possible on the basis of the BHTV data in figure 10H.

[4]This fracture was associated with only a minor amount of outflow during injection; almost all of the outflow in borehole CZ occurred too close to the bottom of the borehole to be logged with the televiewer.

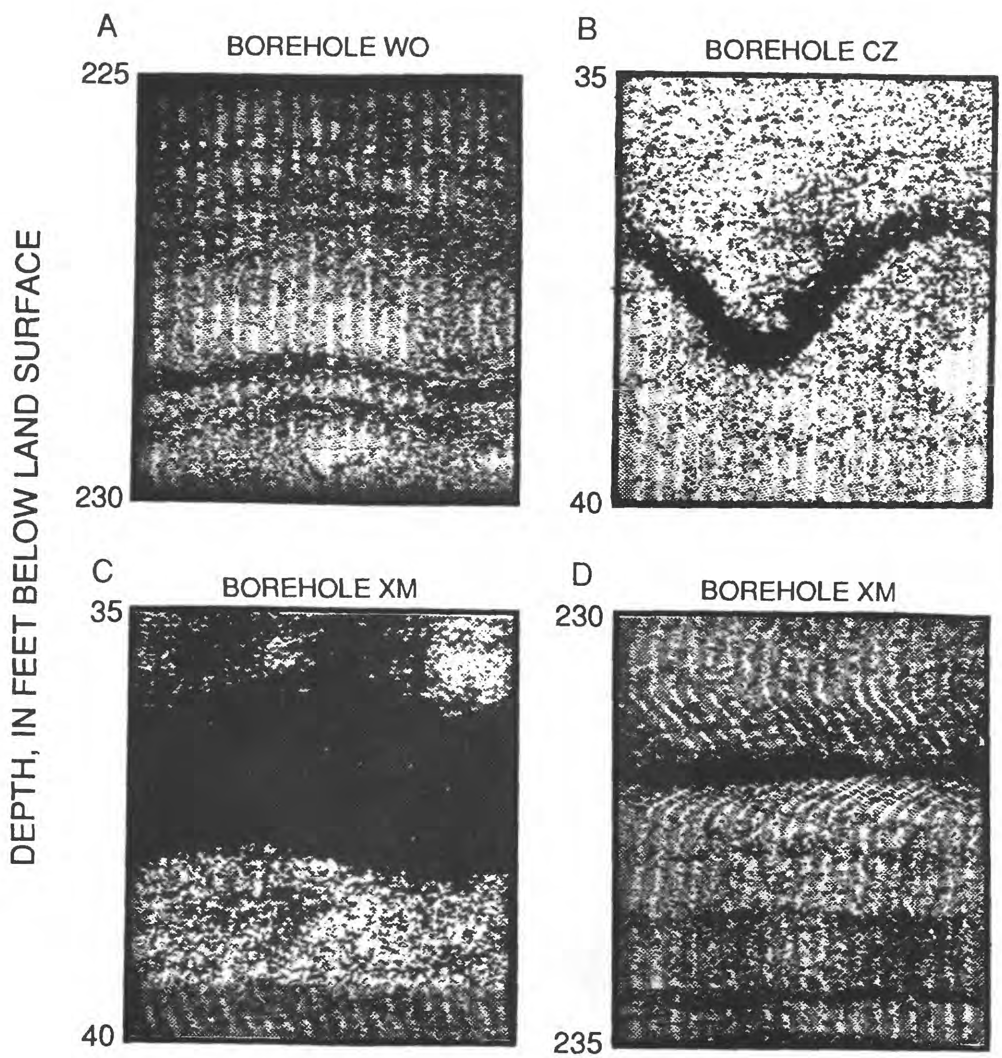

Figure 10. Examples of borehole televiewer logs for (A) foliation planes in borehole WO; (B-H) fractures associated with outflow during recharge in boreholes WO, WI, CZ and XM.

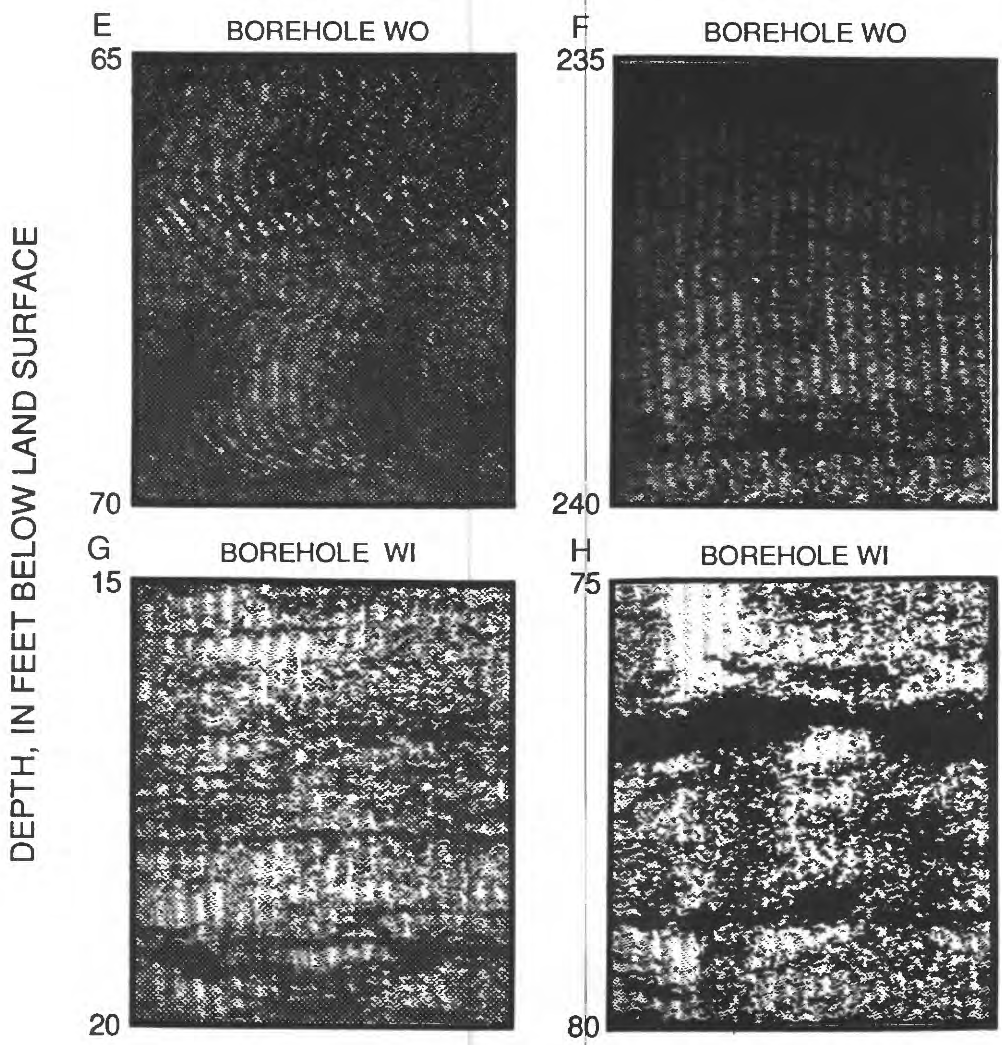

Figure 10. Examples of borehole televiewer logs for (A) foliation planes in borehole WO; (B-H) fractures associated with outflow during recharge in boreholes WO, WI, CZ and XM Continued.

The HPFM measurements made under ambient conditions and during recharge provide information that indicates which of those fractures or other openings identified on the BHTV logs are capable of conducting flow. The HPFM data indicate that only a fraction of the possibly transmissive features on the BHTV logs actually transmit flow. This result is not considered a contradiction of the BHTV interpretation because studies based on fracture flow models indicate that fracture connectivity is as important as local fracture aperture in determining rates of flow through fractured rock bodies (Long and others, 1982).

The population of fractures in the Ashford boreholes identified as capable of producing or accepting flow during hydraulic stressing are summarized in table 1; seven of the eight fractures listed in table 1 are shown in figures 10B-H. At least two other permeable features were intersected by the five boreholes, but these features were located at depths where they could not be logged with the BHTV. Of the eight producing features identified using the BHTV and HPFM during recharge, two are definitely fractures, one could be either a fracture or an opening along foliation, and the remaining five are clearly associated with openings parallel to foliation (table 1). Although there is some variation in local strike of features considered parallel to foliation in table 1, inspection of intervals of BHTV above and below each of these features shows that they are parallel to local orientation of foliation. This can be seen, for example, in figure 10F. These results indicate that subhorizontal fractures and weathering along foliation planes have a major function in the circulation of ground water through bedrock in this part of Ashford. If it is assumed that a population of ten fractures contributes all of the flow into the five boreholes logged at the study site, at least 50 percent and possibly 80 percent of these fractures are parallel to foliation.

The geophysical logs obtained during the Ashford study can be placed in the larger scale context by considering the relation between the fractures identified in each borehole along the transect shown in figure 1. The possible connection between boreholes can be investigated by plotting the orientation of producing fractures and other major features indicated on the BHTV log in the Southwest-northeast plane of the transact (fig. 11). This plot indicates that there are insufficient data to correlate fractures between boreholes at the Ashford site. For example, previous studies of fractured crystalline rocks indicated poor correlation of discrete fractures between boreholes at much smaller separations (Paillet, 1991; Paillet and others, 1987). These studies also indicate that hydraulic connections exist by virtue of fractured rock zones composed of many discontinuous, interconnected fractures. The only consistent pattern in figure 11 is downward decreasing hydraulic heads in the bedrock aquifer at the Ashford study site.

It is inferred that when the 16 wells in the area were intermittently pumped for domestic usage, the downward-decreasing hydraulic heads were even more pronounced. The inverse of the HPFM injection-test data is assumed to indicate borehole flow during pumping (fig. 12), and demonstrates what the flow regime in the five logged boreholes may have been prior to October 1990. If most of the fractures that take part in the flow are parallel to foliation, contaminated ground water could have migrated down the hydraulic gradient along the fracture strike from the point of contamination.

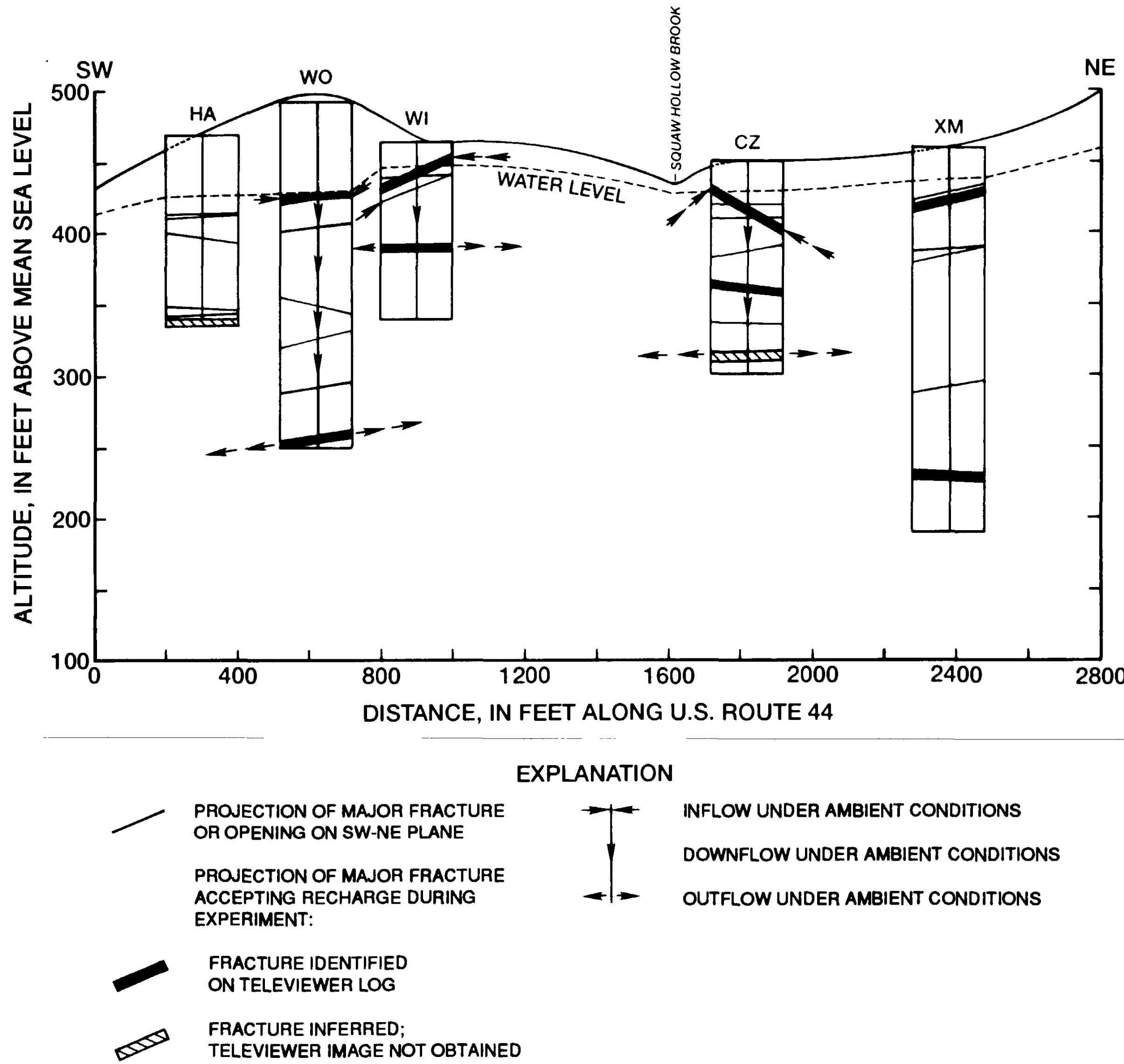

Figure 11. Cross-section through the Ashford study site illustrating flow under ambient hydraulic-head conditions superimposed on projection of fractures identified on the borehole televiewer logs in a vertical plane extending along U.S. Highway 44.

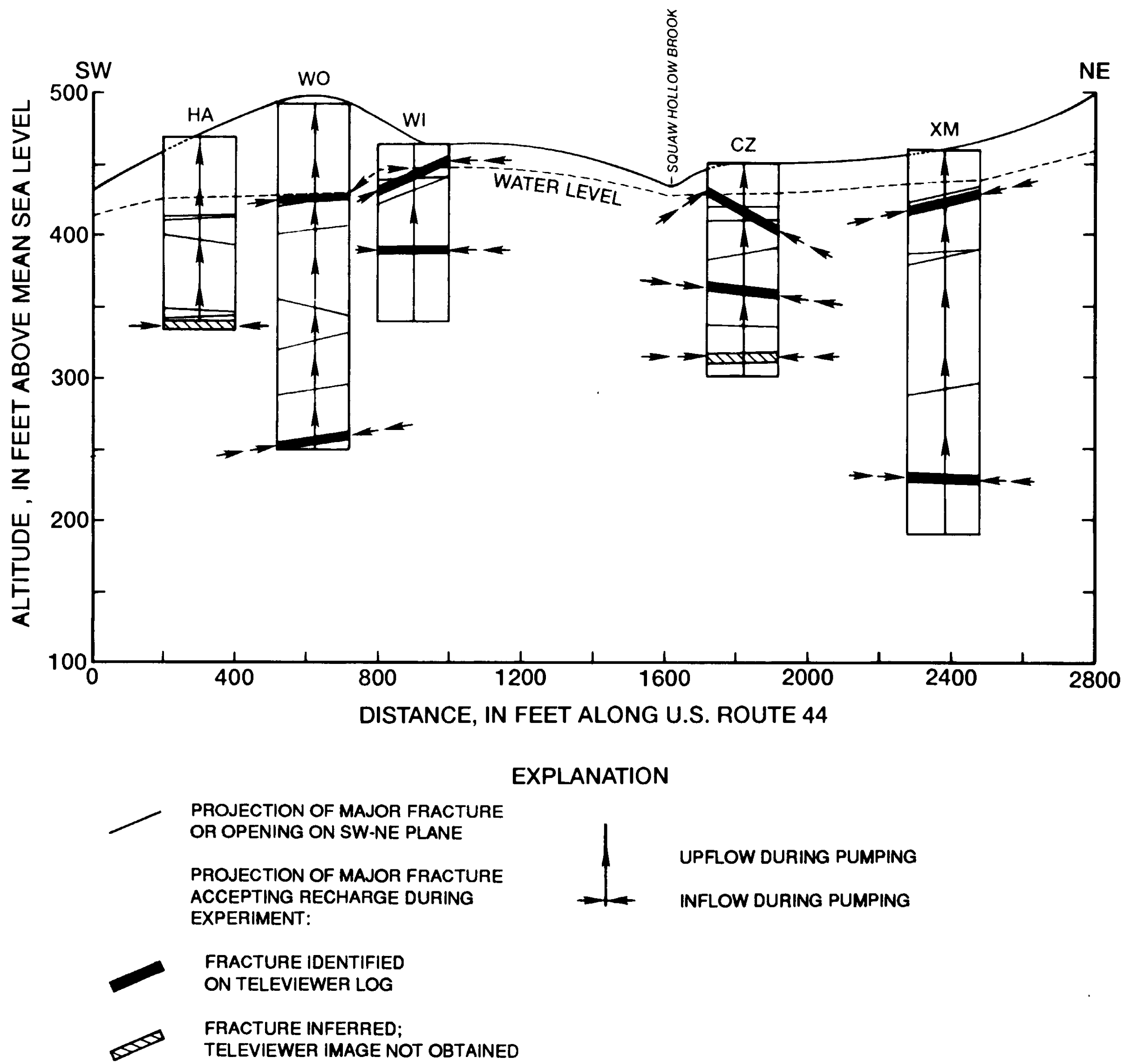

Figure 12. Cross-section through the Ashford study site illustrating flow under steady pumping inferred from recharge tests superimposed on projection of fractures identified on the borehole televiewer logs in a vertical plane extending along U.S. Highway 44.

SUMMARY

Caliper, borehole televiewer, and heat-pulse flowmeter logs were run under ambient conditions and during injection tests at about 1.0 gallons per minute in five boreholes penetrating fractured schist and gneiss at a site in northeastern Connecticut. The logs indicate the depth and orientation of fractures intersecting the boreholes and also indicate which of these fractures produce or accept water under ambient conditions and during injection tests. These results indicate that out of ten producing or accepting fractures eight are identified on televiewer logs; at least five of these fractures are approximately parallel to foliation and to the strike of a regional thrust fault inferred from inspection of surface outcrops. Two producing fractures appear as steeply dipping fractures cutting across foliation, and another may be a fracture across foliation, but this cannot be determined from identified on the televiewer log. Therefore, the orientation of most of the producing fractures is consistent with migration of contamination along the strike of fractures and foliation.

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