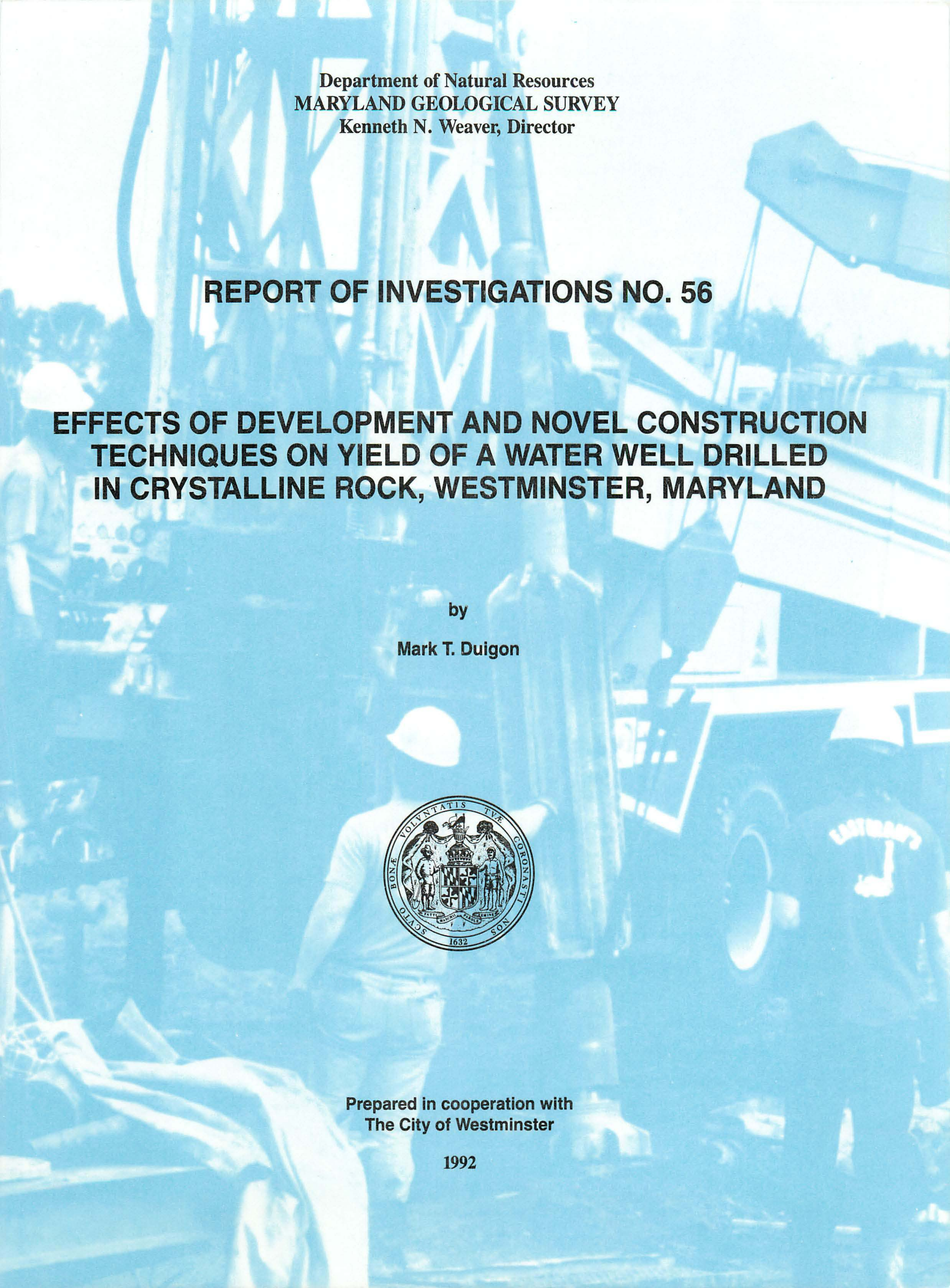

Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 56

EFFECTS OF DEVELOPMENT AND NOVEL CONSTRUCTION TECHNIQUES ON YIELD OF A WATER WELL DRILLED IN CRYSTALLINE ROCK, WESTMINSTER, MARYLAND

by

Mark T. Duigon

Prepared in cooperation with
The City of Westminster

1992

CONVERSION FACTORS AND ABBREVIATIONS

The following factors may be used by those readers who wish to convert the inch-pound units published in this report to International System (SI) units.

Multiply Inch-Pound Unit	By	To obtain International System Unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
ton	907.2	kilogram (kg)
pounds per square inch (psi)	6,895	pascal (Pa)

Chemical concentration and water temperature are given in SI units. Chemical concentration is expressed in milligrams per liter (mg/L) or micrograms per liter (μg/L). Specific conductance of water is expressed in microsiemens per centimeter at 25°C (μS/cm). Water temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) using the following equation:

$$°F=1.8(°C)+32$$

"Sea level" as used in this report refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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COMMISSION
OF THE
MARYLAND GEOLOGICAL SURVEY

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by

Mark T. Duigon

ABSTRACT

The crystalline-rock aquifers underlying most of north-central Maryland are characterized by a strongly skewed well-yield distribution having a preponderance of low values. Municipal and other non-domestic users commonly require higher well yields. Selecting the optimum well site on the basis of topographic or geologic factors improves the odds for obtaining a higher well yield, but often site selection is very constrained; thus the problem becomes how to maximize the well yield attainable at a given site.

Wells completed in the fractured-rock terrane of Maryland are commonly developed simply by blowing compressed air through the drill bit after completion of the well, which may not provide sufficient development. To obtain quantitative data on the efficacy of several methods of well construction and development, a test well was drilled in the crystalline rock in Westminster, Carroll County, Maryland. The methods tested include brushing and surging, hydraulic fracturing, increasing well diameter from 6 to 15 inches, and drilling inclined collectors (rakers).

A 3-inch corehole was drilled initially to a depth of 234.5 feet in order to provide hydrogeologic information for the well site, which is underlain by marble-bearing phyllite of the Sams Creek Formation. The corehole was overdrilled at a diameter of 6 inches to a depth of 254 feet, was brushed and surged, and hydraulically fractured. The hole was again overdrilled, at a diameter of 15 inches to a depth of 241 feet, and was brushed and surged. Two 3-inch coreholes were drilled toward the 15-inch well at inclinations of 45° and 37° for the purpose of improving hydraulic connections between fractures.

Six step-drawdown pumping tests were conducted after various stages of construction and development of the test well using pumping rates ranging from 24.3 to 285 gallons per minute. The results of these tests indicate significant improvements in well yield due to the increase in well diameter from 6 to 15 inches, but no significant changes due to brushing and surging, hydraulic fracturing, or construction of two inclined collectors. The analytical methods of Jacob (1947), Rorabaugh (1953), and Labadie and Helweg (1975) could not be applied to the step-drawdown test results, apparently because of the heterogeneous nature of the hydrologic system under consideration, in which solutional voids strongly influenced ground-water flow in the vicinity of the well. Nevertheless, plots of well characteristics do show semiquantitatively the effects of the yield improvement efforts.

The 6-inch well was pumped at an average rate of 168 gallons per minute for 12 hours. The specific capacity at the end of this period was 8.7 gallons per minute per foot. A second constant-rate pumping test was conducted after the well was enlarged to 15 inches in diameter, brushed and surged, and two rakers drilled. The initial pumping rate of 248 gallons per minute could not be maintained, and after 1,000 minutes dropped off to about 160 gallons per minute. Specific capacity after 12 hours was 6.9 gallons per minute per foot, and after 24 hours was 5.2 gallons per minute per foot. Water-level behavior during this test was characteristic of linear flow. This change in behavior from the test at the 6-inch diameter suggests that the larger diameter well with two rakers, which could produce water more efficiently, very quickly passed through a radial flow regime and into a regime in which a linear geometry (of voids and/or fracture zones) controlled ground-water flow to the well.

A water sample was collected during the second constant-rate pumping test. The water was undersaturated with respect to all common minerals except quartz and contained relatively high concentrations of chloride and nitrate (the likely sources being nearby road salting and agricultural fertilizing)—perhaps reflecting rapid ground-water circulation through shallow weathered rock and cavernous zones.

INTRODUCTION

Wells completed in the crystalline rocks of the Maryland Piedmont and Blue Ridge physiographic provinces not infrequently produce little or no water ("dry holes") or have only marginal production (Dingman and Meyer, 1954; Dingman and Ferguson, 1956; Nutter and Otton, 1969; Otton, 1975, 1979, 1980, 1983; Duigon, 1981a, 1981b, 1983a, 1983b; Duigon and Otton, 1981; Duigon and Dine, 1987). Commercial enterprises and institutions, as well as centralized public-supply systems, commonly require well yields of several tens or hundreds of gallons per minute. Such quantities are greater than what is typically obtained in the Piedmont and Blue Ridge provinces. Most wells drilled in this setting receive no development other than pumping by blowing compressed air through the drill bit upon completion of drilling. Well development (the clearing of ground rock fragments from the fractures and voids that open to the well, and the increasing of formation permeability in the vicinity of the well) could increase the yields of some crystalline-rock wells.

PURPOSE AND SCOPE

The chances for obtaining an adequate well yield can be enhanced by selecting a favorable site for constructing the well (Ellis, 1906; Dingman and Meyer, 1954; Meyer, 1958; LeGrand, 1954, 1967; Nutter and Otton, 1969; Nutter, 1974, 1977; Duigon and Dine, 1987). However, site selection may be severely limited, and perhaps the only available site is not very favorable. How can maximum yield be obtained from a less-than-optimum site? The purpose of this report is to describe well-construction and development techniques that may be used to maximize yields of wells drilled in crystalline rocks, and to discuss the geohydrologic factors affecting the efficacy of these techniques. Survey results of the literature and well-completion records are summarized, and construction and testing of an experimental well are analyzed. The experimental well was constructed and developed in stages, and tested after each stage to evaluate the techniques involved. The techniques were increasing well diameter, drilling of coreholes inclined toward the central well (rakers), brushing and surging, and hydraulic fracturing. Site-selection factors (discussed elsewhere) are addressed in this report only insofar as they bear on analysis of the effects of well development and stimulation.

AREA COVERED

Crystalline rocks occur at or near the surface in about 30 percent of the land area of Maryland (fig. 1), underlying the Blue Ridge and most of the Piedmont physiographic provinces. The main lithologies present comprise metasedimentary, meta-igneous, and igneous rocks. Detailed descriptions of the rocks and maps showing their distributions are provided by various county maps and reports published by the Maryland Geological Survey. These sources, as well as others, were compiled by Vokes and Edwards (1957) and for the state geologic map (Cleaves et al., 1968). More recent work includes reinterpretations of the stratigraphic framework of the crystalline rocks near Baltimore (Crowley, 1976) and of Cecil County (Higgins, 1990). A number of quadrangle geologic maps (scale 1:24,000) covering areas of the Piedmont and Blue Ridge physiographic provinces have been published by the Maryland Geological Survey since 1974.

METHODS OF STUDY

Well data were retrieved from the U.S. Geological Survey's national computerized database. This database includes site, construction, and yield information gathered for wells inventoried as part of numerous projects in Maryland. Quantitative data useful for assessing the efficacy of well-development and stimulation techniques in Maryland are virtually nonexistent, so a test well was drilled and selected construction, development, and stimulation techniques were applied and tested.

PREVIOUS INVESTIGATIONS

A survey of well stimulation was presented by Koening (1960), examining 483 wells in 24 states. That study covered a broad variety of geologic settings, and did not address well hydraulics. A non-quantitative summary of well development techniques was presented by "Jeremiah" (1986); methods specifically suggested for rock wells were wire brushing, surging, hydraulic fracturing, and use of explosives.

The mechanics and effectiveness of blasting were discussed by Ebaugh (1950) and Mylander (1952). The technology of explosives has improved since then, although simple (but potentially dangerous) methodologies are still described (e.g., Driscoll, 1978). The expansion and implosion of bubbles produced by explosives brings to mind the bubbling action of frozen carbon dioxide, or dry ice, which has been used to develop rock wells (Goodwin, 1978; a picturesque description in the popular literature by Pruett, 1982).

Since the late 1940's, the petroleum industry has been enhancing fluid transmission in rocks by injecting water under high pressures. Hydraulic fracturing was found to be successful in stimulating water wells in crystalline rock (Stewart, 1974), and has received greater attention, especially in recent years (Waltz and Decker, 1981; Baski, 1987; Hurlburt, 1989).

Drilling a larger diameter well obviously can increase the amount of water derived from borehole storage, but some workers have noted increases in yield exceeding what would be predicted by the Thiem equation. Norris (1976) believed that increasing the diameter of a well drilled in dolomite allowed larger parts of cavities to be opened to the borehole. Caswell (1985, 1987) attributed larger than expected yield increases to better development in the larger diameter wells (while also mentioning the possibility of increased surface area of fractures intersected by the boreholes). Atkinson and Gale (1985) applied a quasi-deterministic numerical model to study the nature of well losses

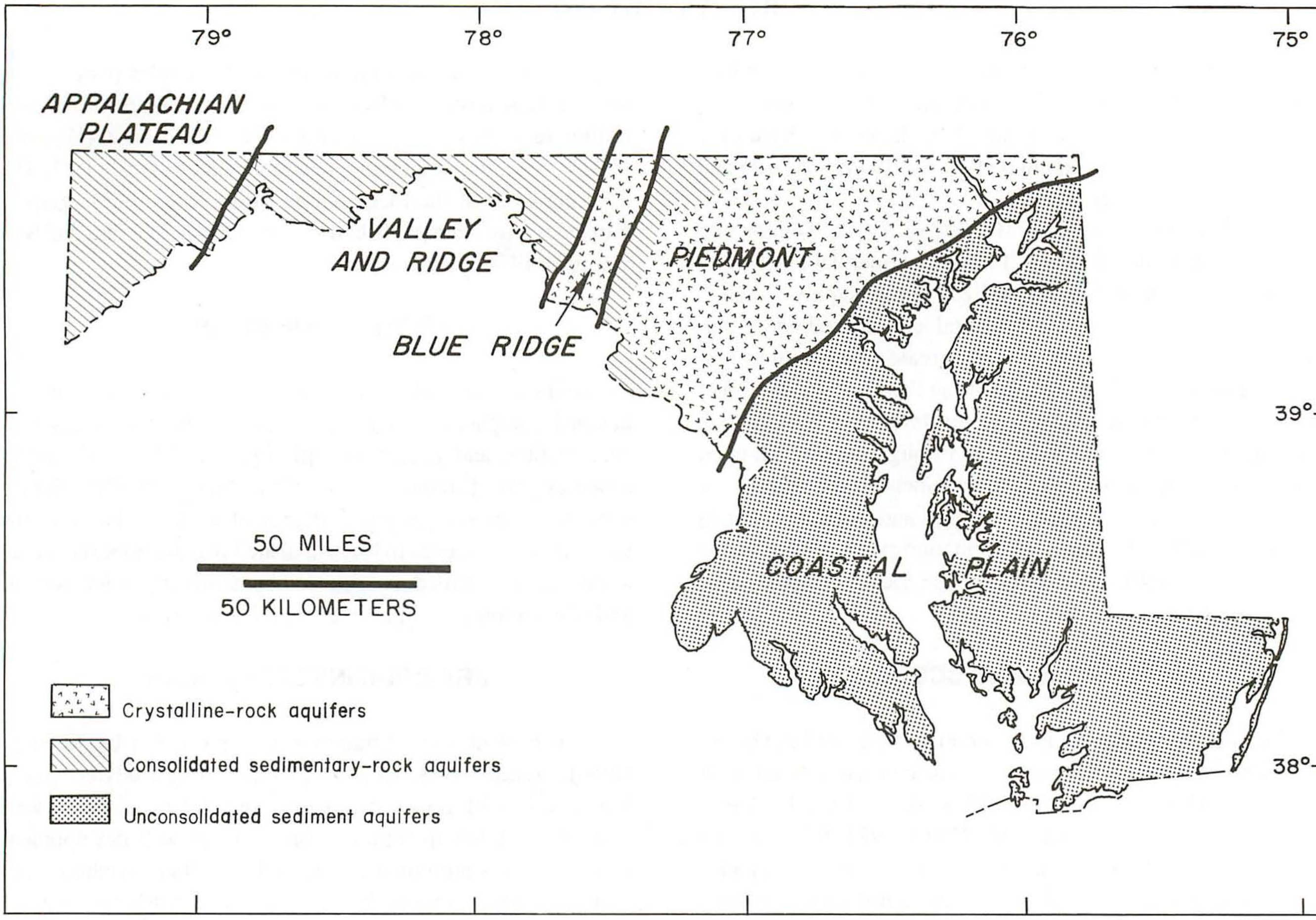


Figure 1.—Physiographic provinces and principal aquifer types of Maryland.

and the effect of increasing well diameter, and it calculated significantly greater production rates than those predicted from the logarithm of the ratio of the radii.

Another practice that has become routine in the oil-drilling industry, but has only been experimentally applied to water wells, is controlled-directional drilling. Drilling accuracy has been demonstrated (Kravits et al., 1987); selecting the best direction to optimize production in fractured reservoirs has been discussed by Nolen-Hoeksema and Howard (1987). Generally applied to drilling thin sedimentary formations for oil or gas production, horizontal drilling can be done from short (47 to 71 ft) vertical starts with a tight radius of curvature (as little as 30 ft) (Mahony, 1988). This method, in principle, could be applied to municipal or commercial well drilling, but specialized equipment and skills render it prohibitively expensive for routine use for the present.

Day et al. (1978) investigated the effects on yield of inclined holes drilled as collectors leading to a large-diameter (39 in.) central well constructed in a fractured-chalk aquifer. Three such holes, inclined at 45°, more than doubled the yield.

ACKNOWLEDGMENTS

This investigation was undertaken in cooperation with the city of Westminster. William Mowell, Department of Public Works, facilitated access and preparation of the test site. Danny Easterday, L. F. Easterday Inc., applied much expertise to the construction of the test well. Geophysical logs were run by Gerald Idler, U.S. Geological Survey (USGS). The manuscript was reviewed by Dennis W. Risser, USGS; Claire Richardson, USGS (ret.), and Kenneth R. Bradbury, Wisconsin Geological and Natural History Survey.

AVAILABILITY AND USE OF WATER IN THE CRYSTALLINE-ROCK TERRANE OF MARYLAND

SOURCES OF WELL DATA

The State of Maryland has required a permit for water-well construction since 1945. The permit application and the completion report provide helpful information concerning the availability of ground water (fig. 2). Most of the well construction and yield data were obtained from completion reports of the wells that have been inventoried in the area. Additional yield data were obtained from the files of the Maryland Geological Survey, the Maryland Water Resources Administration, and from the U.S. Geological Survey. Site information, such as precise location and topographic setting, was obtained from field checking and mapwork.

Well-yield testing has evolved over the years as the need for accurate information has been recognized. The State now requires a rigorous protocol for testing wells in the Piedmont. Eyeball estimates of abstraction rates, where withdrawals are accomplished by bailing or blowing with air, have been replaced by volumetric measurements where submersible pumps are used; water levels are being measured using electric sounding tapes rather than being estimated by the approximate position of the drill bit.

WELL-NUMBERING SYSTEM

Wells and springs that have been inventoried for the Maryland Geological Survey's ground-water data base are identified using a statewide numbering system in which each identifier consists of three parts. The first part is a two-letter abbreviation for the county in which the well is located. A separate grid system is set up for each county, based on five-minute intervals of latitude and longitude. Each square of the grid is identified alphabetically by tier and column beginning at the northwest, providing the second part of the identifier. The third part of the identifier is a sequence number for the well or spring. For example, well CL Bd 175 is located in Carroll County, the second tier and fourth column of the grid, and is the 175th well or spring inventoried in that quadrangle.

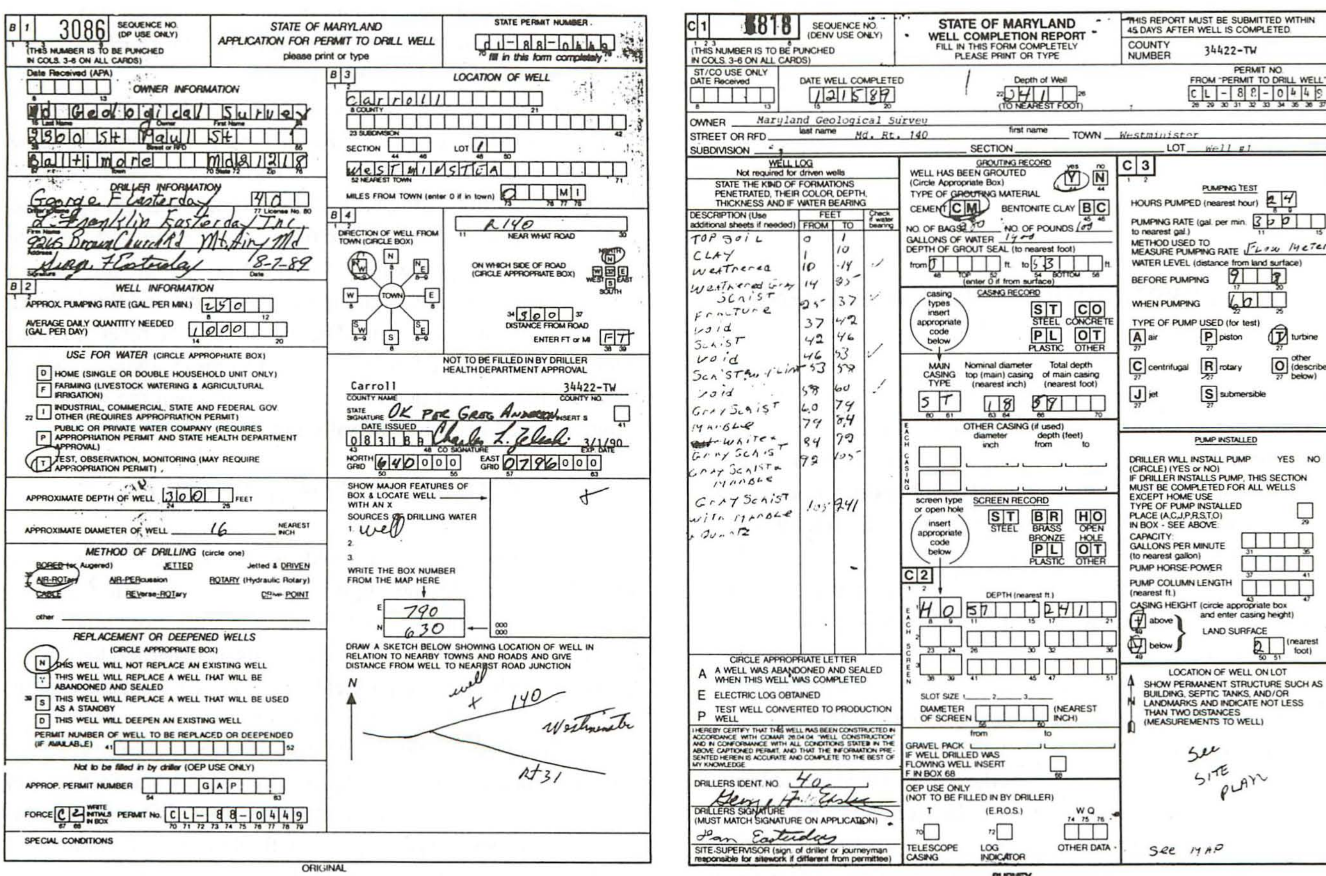


Figure 2.—Water-well permit application (left) and completion report (right).

CATEGORIES OF WATER USE

Crystalline rocks supply approximately 20 percent of the ground water withdrawn in Maryland, which totalled 242 million gallons per day in 1986 (Wheeler, 1990). Most wells drilled in crystalline rock in Maryland are used for domestic supply (table 1). Yields of 1 or 2 gal/min are generally sufficient for such purposes and in most areas are readily obtained, thus little importance is placed on selecting the optimum well site or utilizing more expensive and difficult construction or development procedures. Other categories of water use place a wide range of demands on water supply (U.S. Environmental Protection Agency, 1982, tables 1 and 2), and some users in these categories can justify the additional expenses needed to meet higher demands.

Table 1.—Ground-water use in the Piedmont and Blue Ridge physiographic provinces [Data from U.S. Geological Survey Ground-Water Site Inventory; number of inventoried wells with known uses is 6,280]

Use	Percent
Domestic	70.9
Public supply and institutional	6.5
Commercial	3.9
Stock and irrigation	1.7
Other	2.6
Unused	14.5
Total	100.1

WELL CONSTRUCTION AND DEVELOPMENT PRACTICES

Wells completed in crystalline rock in Maryland generally are constructed using air-percussion drills (fig. 3). Air-percussion drills use compressed air to cause a bit hammer to reciprocate in a rapid, short-throw manner. This pounding process produces a powder that allegedly is blown into the fractures that transmit ground water to the borehole, thereby partially clogging them. To avoid this condition, some owners prefer to have their wells constructed by cable-tool drilling rigs, which they believe produce greater yields. Reported yields of wells drilled by cable rigs do tend to be greater than those of wells drilled by air-percussion rigs (fig. 4); significance level <0.001 by Mann-Whitney U-test (SPSS Inc., 1988). However, these results may reflect a bias in the data—many of the wells drilled by cable rigs predate yield-testing regulations and the trend to build housing developments on hilltops; thus, well sites are generally more favorable and estimates of yield may be optimistic in the case of wells drilled by cable rig.

TOTAL NUMBER OF WELLS: 6,122

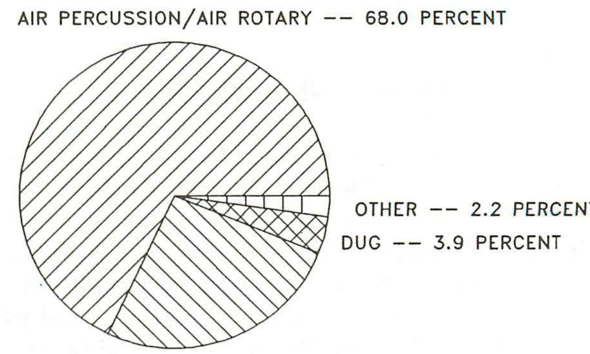


Figure 3.—Methods of constructing water wells in crystalline rocks in Maryland.

After reaching the final depth of a well drilled by air-percussion, the well is commonly developed by air-lift pumping. This is accomplished by leaving the tools in the well and blowing compressed air out of the bit. The casing serves as the eductor (outer pipe), and the drill string serves as the air line (inner pipe). This method of well development is most efficient when the ratio of the submerged length of air line to the total length of air line is about 60 percent and the air line can be raised inside the eductor for pumping and lowered below it for surging (Johnson Division, UOP, Inc., 1975, p. 304).

A number of well-drilling companies that operate in the Maryland Piedmont and Blue Ridge have been offering hydraulic fracturing in the last few years. The method commonly used consists of setting a single mechanical packer in the open-hole zone 10 to 15 ft below the bottom of the casing and injecting water at a rate of approximately 100 gal/min. If the formation is tight, the pressure may build up over 1,000 psi and then quickly decrease if a fracture opens. The packer may be reset at greater depth and the procedure repeated. Propping agents (such as sand, added to the injected water to prop open the induced or enlarged fractures) are generally not used.

DISTRIBUTION OF WELL YIELDS

The distribution of well yields reported for the study area is strongly skewed to the right (higher yields are increasingly scarce) (fig. 5). There is a bias in the data away from high values because the bulk of the inventoried wells were drilled for domestic use, for which minimal yields are acceptable. If only industrial, institutional, and public-supply wells are considered, reported yields tend to be higher (fig. 6). Productivity (yield and specific capacity) of wells grouped by various site factors such as lithology and topographic setting exhibits different distributions, but this study is concerned with obtaining maximum well yield for a given site, assuming that the site factors cannot be controlled.

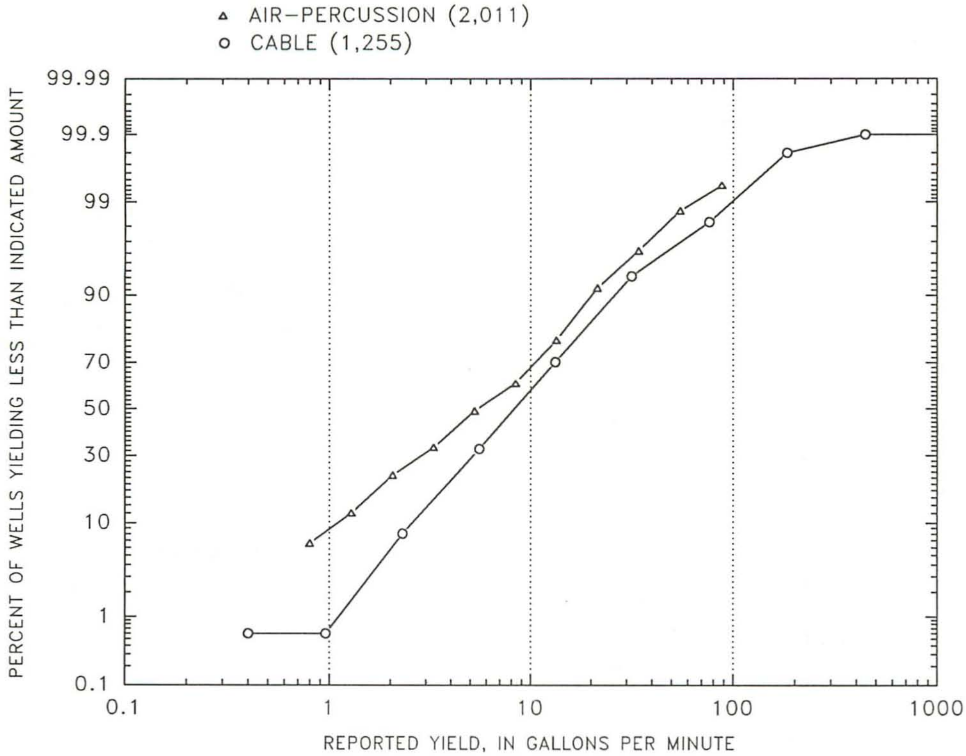


Figure 4.—Cumulative frequency distributions of yields of wells drilled by cable tool and by air percussion methods. Curves are based on data for wells drilled in crystalline rock in Maryland by these two methods.

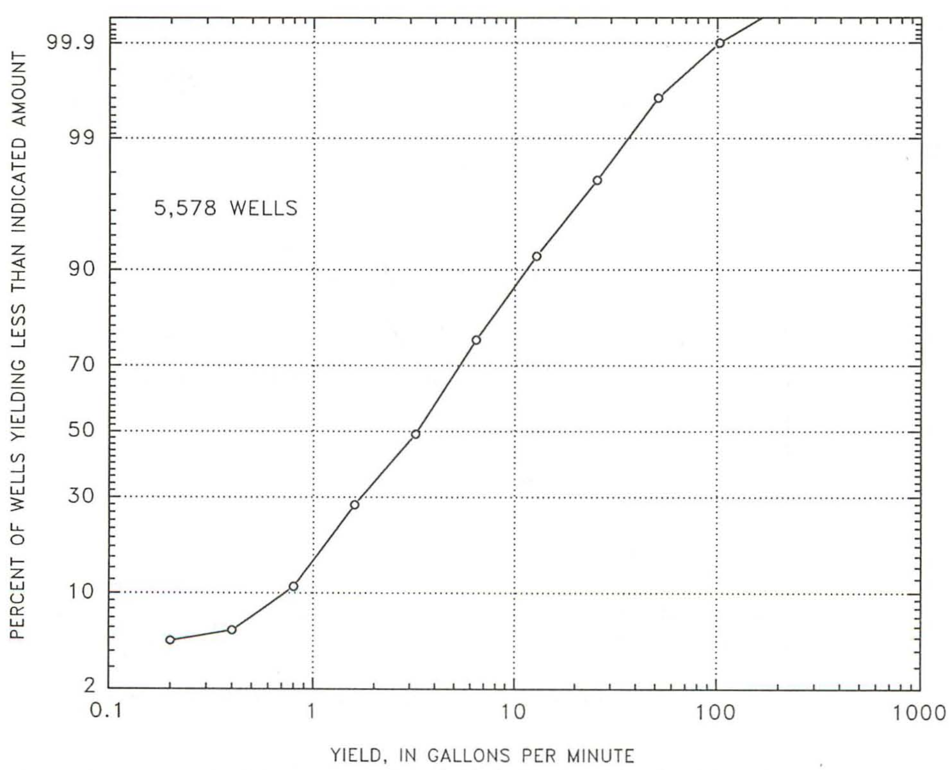


Figure 5.—Distribution of reported yields of wells in crystalline rocks in Maryland.

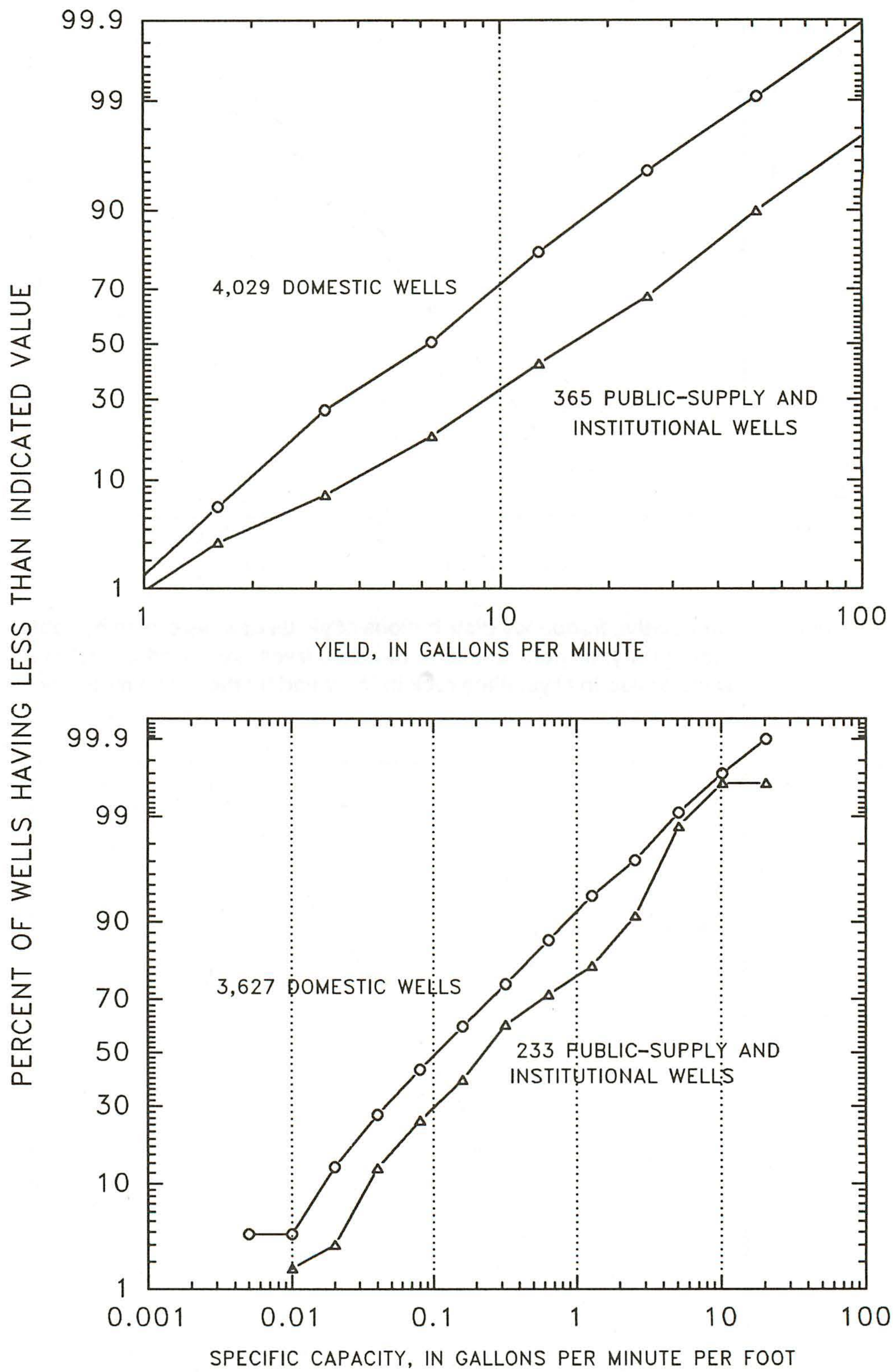


Figure 6.—Cumulative frequency distributions of yields and specific capacities of industrial, institutional, and public-supply wells and of domestic wells.

HYDROLOGY OF CRYSTALLINE ROCKS

OCCURRENCE AND MOVEMENT OF GROUND WATER IN CRYSTALLINE-ROCK TERRANE

The unifying hydrologic characteristic of crystalline rocks is the interlocking nature of their mineral grains, which results in negligible primary porosities. Fractures and other secondary voids provide essentially all of the porosity necessary to permit the occurrence of ground water in these rocks, and the degree of interconnectivity of these voids governs permeability. Specific types of rock fractures include faults, in which the rock on one side of the fracture plane is displaced relative to the other side; and joints, which show no appreciable displacement.

Faults may facilitate or impede ground-water flow. In some cases additional fractures may be present in the vicinity of the fault plane; in other cases the grinding action of rock movement and subsequent weathering may produce a clayey, impermeable medium. Nutter and Otton (1969, p. 17–18) found only one out of nine wells along faults in the Maryland Piedmont had a greater than average yield (that well penetrated the crystalline Ijamsville Formation and the noncrystalline New Oxford Formation). Nutter (1977, p. 16) found the average yield of 17 crystalline-rock wells along faults in Harford County was higher than average for the county, although some individual yields were lower than the county average.

Joints commonly occur in closely-spaced, regular, parallel sets. Multiple sets (sets having different orientations) are generally present in igneous and metamorphic rocks. Joint attitudes can correlate with various other structural features such as fold axes, schistosity, and foliation and can vary from horizontal to vertical (Cloos, 1964, p. 254–255). Attitudes of exposed fractures in metamorphic rocks in Maryland and elsewhere are commonly steep (Pincus, 1951; Nutter and Otton, 1969, p. 17). Surface expression of vertical fractures or fracture zones in dissected terrain is linear, which makes them recognizable on aerial photographs and topographic maps. Fracture traces are linear features less than one mile long that are observable on aerial photographs (Lattman, 1958, p. 569). They include alignments of topographic, soil-tone, and vegetational indicators of vertical planes of fracture, as well as straight stream reaches (Setzer, 1966). The azimuths of joint sets has been found to correlate with straight stream reaches in the Maryland Piedmont (Nutter and Otton, 1969; Nutter, 1977).

Rock fractures commonly are products of nonuniform geologic stresses acting on media having anisotropic properties; consequently, hydrologic properties such as the secondary permeability provided by fractures is characteristically anisotropic and heterogeneous. This condition can confound the determination of transmissivity from aquifer tests and other aspects of ground-water behavior.

Where fractures are few and widely scattered, it may not be appropriate to treat the fractured medium as an equivalent porous medium. An alternative approach suitable for some hydrologic analyses treats fractures as pairs of parallel plates. However, fracture planes are not flat and smooth. Under conditions of elevated stress, constriction of a fracture produces anastomosing "channels" through which ground water can be conducted, because of the relief of the fracture walls (Tsang and Tsang, 1987). A discrete-fracture approach requires data for fracture numbers, location, length, orientation, aperture, and roughness. These factors can rarely be determined at a well site; in some cases, data may be synthesized from statistical characteristics of observable fractures, but such techniques are beyond the needs of selection of optimum sites for high-yield wells.

Aquifer properties in the crystalline-rock terrane of Maryland are commonly evaluated using water-level measurements made in a single pumping well; one or more observation wells are generally not available. Values of transmissivity obtained under these circumstances can be useful for hydrologic reconnaissance and where broad estimates are acceptable; however, depending on the nature and scale of the problem, their use can lead to serious misinterpretations of hydrologic behavior. Storage coefficient cannot be estimated from single-well tests by the usual methods. Published values of transmissivity and storage coefficient range over more than two orders of magnitude; transmissivity generally does not exceed 1,000 ft^2/d, and storage coefficients are generally less than 0.01 (table 2).

WELL-AQUIFER RELATIONS IN CRYSTALLINE-ROCK TERRANE

The hydraulics of ground-water flow to wells is affected by the anisotropy and heterogeneity typical of crystalline-rock aquifers. Some analytical solutions, particularly those based on the methods of Theis (1935) or Jacob (1950), were developed for ideal isotropic and homogeneous media and yield results that are significantly in error when applied to fractured crystalline-rock aquifers.

In the case where a well bore intersects a small number of significant water-bearing fractures, the concept of the borehole acting as a line sink in a uniform medium is not realistic. Using an average permeability may permit analysis of well hydraulics for some situations; for other situations, using individual fracture transmissivities may provide more useful results. The effects of significant fractures on average permeability can be incorporated in digital models used for analysis of pumping tests (Rushton and Redshaw, 1979, p. 276–277).

DRAWDOWN BEHAVIOR IN A PUMPING WELL

The effect of well radius on yield is incorporated in the Thiem equation (Davis and DeWiest, 1966, p. 202),

$$H - h = \frac{Q}{2\pi Kb} \log_e \left(\frac{r_e}{r}\right)$$

Table 2.—Transmissivities and storage coefficients from aquifer tests of crystalline rocks

[Sources: 1, Overbeck and Slaughter, 1958; 2, This report; 3, Meyer, 1958; 4, Duigon and Dine, 1991; 5, Slaughter, 1962; 6, Nutter and Otton, 1969; 7, Otton, 1981; 8, Dingman and Ferguson, 1956; 9, Data from Md. Geological Survey files; 10, Data from R.E. Wright Assoc., Inc., 1987; 11, Data from Md. Water Resources Administration; 12, Data from Md. Dept. of General Services]

Geologic unit	Transmissivity ($feet^2$/day)	Storage coefficient	Test wells	Source
Baltimore Mafic Complex (Gabbro)	1,872	0.003	CE Ac 38, 39, 40	1
Sams Creek Formation (Phyllite with marble)	1,269 - 1,643	--	CL Bd 175	2
Sams Creek Formation (Wakefield Marble)	6,952	.004	CL Ce 2, 3	3
Catoctin Formation (Metabasalt)	29	--	WA Al 9	4
Marburg Formation	976	.02	FR Eh 1, 2	3
Harpers Formation	67	--	WA Bk 11	5
Morgan Run Formation	227 - 869	.003 - .12	MO Cf 18-22	6
Ijamsville Formation	71	--	MO Cd 47	7
Prettyboy Schist	428	--	BA Ca 7	8
Prettyboy Schist (calcareous zone)	17	--	CL Bf 184	9
Prettyboy Schist	5,880 (maximum) 1,470 (minimum) 2,940 (geometric mean)	.01	Test well 7, Test well 3, Test well 5, Monitoring well 4, Monitoring well 6	10
Prettyboy Schist	18 - 106	--	BA-73-8284 BA-81-0033	11
Harpers Formation	263	--	FR Bd 30	9
Metagabbro	112	--	HA De 37	9
Marburg Formation	670	--	FR Eh 10	7
Prettyboy Schist	12	--	CL Ec 75	7
Prettyboy Schist	668	.03	CL Bf 17	3
Sykesville Formation	201 - 374	.002	MO Cf 23, 24	6
Loch Raven Schist (Hydes Marble Member)	4,679	--	BA Df 39	8
Baltimore Gneiss	307 - 709	--	BA Cc 27	8
Baltimore Gneiss	20	--	BA-81-0224	12

which has as a term the logarithm of the ratio of the radial distance to zero drawdown (radius of influence, r_e) over the radial distance at which drawdown is measured (in this case, the radius of the well, r). The other terms of the equation are thickness of the aquifer, b; distance from the base of the aquifer to static level, H; distance from the base of the aquifer to pumping level, h; hydraulic conductivity, K; and discharge, Q. In the case of an unconfined aquifer, where b is not constant, the relations may be expressed as

$$H^2 - h^2 = \frac{Q}{\pi K} \log_e \left(\frac{r_e}{r}\right)$$

(Davis and DeWiest, 1966, p. 204).

The equations can be rearranged to solve for Q and plotted using assumed values for the various parameters to visualize the effect of well radius on yield (fig. 7). For the example in the figure (unconfined aquifer version), the assumptions are

$H = 200$ ft
$h = 150$ ft
$r_e = 400$ ft
$K = 5$ ft/d (open circles)
$K = 2.5$ ft/d (solid circles).

As the figure shows, doubling the well-radius results increases the yield by almost five percent (from 108 to 113 gal/min on the lower line, in changing radius from 3 to 6 inches). A doubling of aquifer hydraulic conductivity, on the other hand, doubles well yield.

A host of simplifying assumptions are usually made when aquifer properties are estimated by analysis of pumping tests. Some of these assumptions refer to the aquifer, and some refer to the well or wells. Factors that affect the rate of drawdown are listed in table 3.

The Thiem equation considers only linear head loss resulting from laminar flow in the formation; total drawdown in a pumping well includes nonlinear head loss due to flow in a turbulent zone in the vicinity of the well, loss resulting from water moving from the formation into the well bore (exit loss), and loss due to flow in the well bore toward the pump intake. The two latter head losses are inversely related to higher powers of well radius (Atkinson and Gale, 1985, p. 75). There is a critical discharge rate at which turbulence develops in the vicinity of the well bore. The nonlinear losses are collectively termed well loss. Well loss can comprise a significant portion of total drawdown and is therefore of concern in the design of wells to meet high water demands.

Table 3.—Factors affecting rate of drawdown in a pumping well

AQUIFER FACTORS	*WELL FACTORS*	*OTHER FACTORS*
Transmissivity	Borehole storage	Time
Storage coefficient	Partial penetration	Meteorological changes
Anisotropy	Pumping rate	Pumping from nearby wells
Heterogeneity	Well efficiency	
Boundaries		
Leakage		
Water-table conditions		
Vertical flow		
Fracture skin		

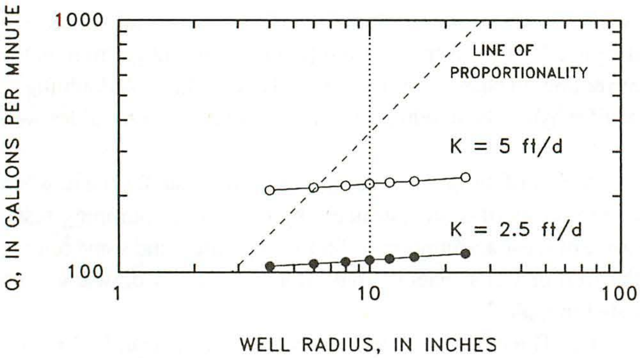


Figure 7.—Relationship of well yield and well radius. The two lines are based on the Thiem equation (unconfined aquifer version) with assumed values (see text) for the equation parameters.

The only factors listed in table 3 that can be controlled at a given well site are the well factors; manipulation of some of these can improve well yield. *Borehole storage* appears on a log-log plot of drawdown versus time as a straight-line segment of unit slope for the early portion of a pumping test. Drilling a deeper or larger-diameter well can increase the amount of water in temporary storage, but periods of non-pumping are required to replenish it.

Partial penetration complicates drawdown behavior because many analytical techniques assume horizontal flow through the entire thickness of the aquifer. When wells only partially penetrate the aquifer, vertical flow occurs, which violates the analytical assumptions and can allow further complications due to aquifer anisotropy and heterogeneity. However, wells in crystalline-rock aquifers can usually be constructed as open-hole wells through the hydrologically significant portion of the formation (generally the upper several hundred feet).

An increase in *pumping rate* causes a greater increase in drawdown than predicted by equations which assume the well is a line sink, owing to additional losses incurred by turbulent flow (Darcy's law is inapplicable to turbulent-flow regimes). Whereas drawdown resulting from formation losses is proportional to discharge, drawdown due to well losses varies approximately with the square of discharge. *Well efficiency* is a measure of the portion of total drawdown in a pumping well that is due to well factors rather than aquifer factors. (Drawdown in a 100-percent efficient well would be due entirely to formation losses.) Well efficiency can be optimized by maximizing the area open to the aquifer (suitable screens, where well screens are used) and development to minimize exit losses and losses due to turbulent flow near the well bore.

Water level in a "typical" well in a fractured crystalline-rock aquifer characteristically responds to pumping in the manner shown in figure 8. Every segment of the curve shown in the figure may not be present in all wells drilled in fractured crystalline rocks, and some segments may be repeated, depending on the well–aquifer geometry. At earliest times, water is derived entirely from borehole storage; hence segment A-B is linear with unit slope on the log-log plot. As water from the aquifer moves into the well, the curve follows the Theis solution if flow is radial (segment B-C). If a vertical fracture or zone of high permeability is present, ground water can flow perpendicularly into this zone and then toward the well, and linear flow (fig. 9) prevails, characterized by a slope of 0.5 (segment C-D). As the cone of depression reaches the boundary of the high permeability zone, the zone is dewatered, and the curve becomes linear with unit slope again (segment D-E). This condition is sometimes referred to as "pseudo-steady state"—it is actually unsteady-state flow, but the shape of the potentiometric surface remains constant as it is uniformly lowered throughout the aquifer.

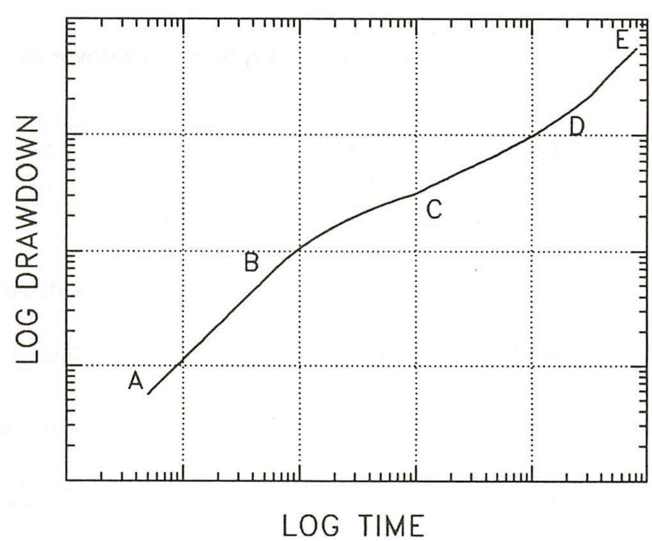


Figure 8.—Water-level response in a "typical" well drilled in fractured crystalline rock.

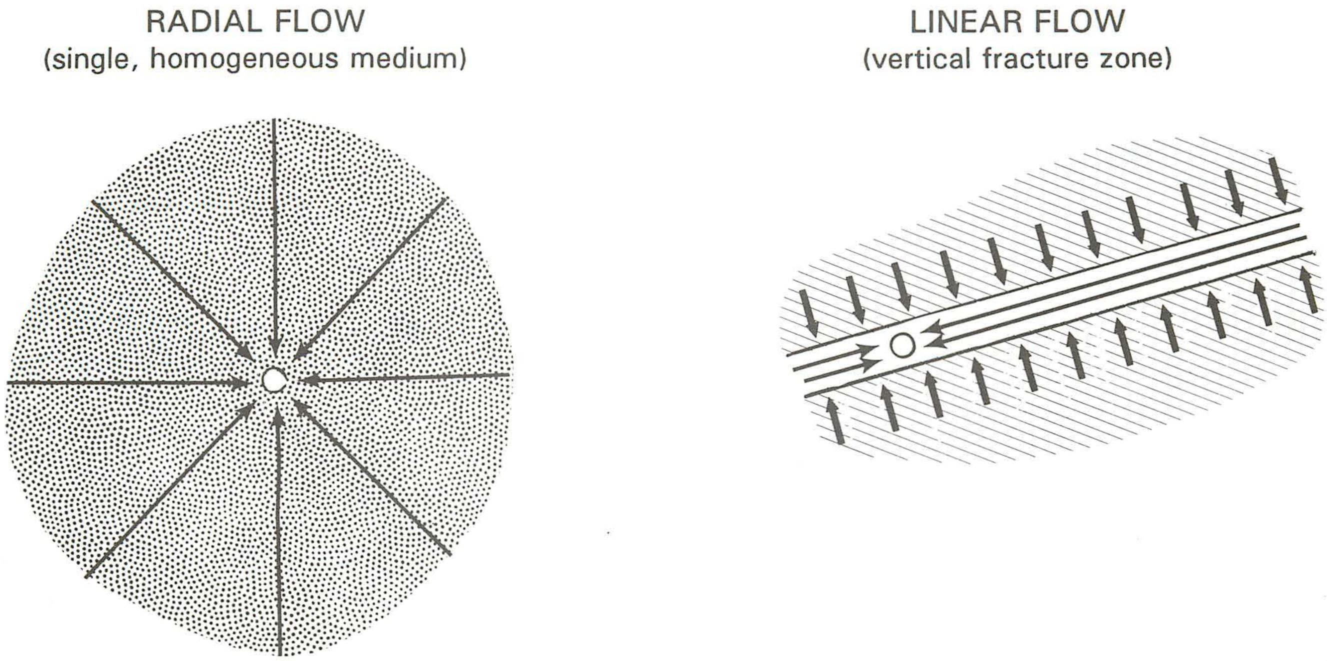


Figure 9.—Radial flow and linear flow to a well. Arrows indicate ground-water flow paths.

WESTMINSTER TEST WELL

A test well was constructed in order to obtain quantitative data on the efficacy of well development and stimulation techniques. The same hole was overdrilled to assess the effects of the change in diameter on well productivity. Brushing and surging were conducted in the well at both diameters, and hydraulic fracturing of the 6-in. hole was performed. Two inclined coreholes (rakers) were drilled to act as collectors, with the assumption that they would intersect additional near-vertical water-bearing fractures. Well productivity was tested by means of step-drawdown pumping tests after each procedure was completed.

DESCRIPTION OF THE TEST WELL SITE

The test well site is located in northwestern Westminster, Carroll County, Maryland (fig. 10). The area had been under consideration by the city as a possible well site, but no test drilling had yet been done. Relief of the site is about 75 ft, descending from Md. Route 140 northwestward toward a small tributary of the Meadow Branch of Big Pipe Creek (fig. 11). The test well is located near the top of the foot slope, about one third of the way up the hillslope.

The test site is underlain by the Sams Creek Formation (Fisher, 1978), which is described by Fisher on the New Windsor Quadrangle as a "[s]chistose to massive greenstone interlayered with green to blue chlorite phyllite and minor gray hematite-muscovite phyllite." The Sams Creek Formation consists of metamorphosed lava (metabasalt) and associated rocks. Fisher (1978) makes no mention of calcite within the Sams Creek Formation, but did map the Wakefield Marble nearby. Stose and Stose (1946, p. 64) described the appearance of the weathered metabasalt as "worm-eaten" where calcite that had filled amygdules had been removed; the upper, weathered zone penetrated by the test well had a similar appearance (fig. 12). Edwards (1986), who mapped the Union Bridge Quadrangle adjoining the western edge of the New Windsor Quadrangle, placed the Wakefield Marble as a member within the lower part of the Sams Creek Formation; he also noted additional calcite and marble throughout the Sams Creek Formation, some of which may be part of the Wakefield. A diabase dike is located about 300 ft northwest of the test well, running north-northeast—south-southwest (Jonathan Edwards, Jr., Maryland Geological Survey, 1989, personal communication).

The general structural trend in the vicinity of the test site is northeast-southwest. Crenulation cleavages generally strike northeast (Fisher, 1978). No significant faults are located in the vicinity, although minor faults were noted in the test core (fig. 13). The minor faults apparently are well-healed and do not constitute zones of significantly different permeability.

A few fracture traces are visible on a stereographic pair of aerial photographs of the test site (fig. 14). Fracture traces are linear features less than 1 mi long that presumably are the surface expression of vertical zones of rock fracture. They may be evidenced by straight stream reaches, alignment of soil tonal or

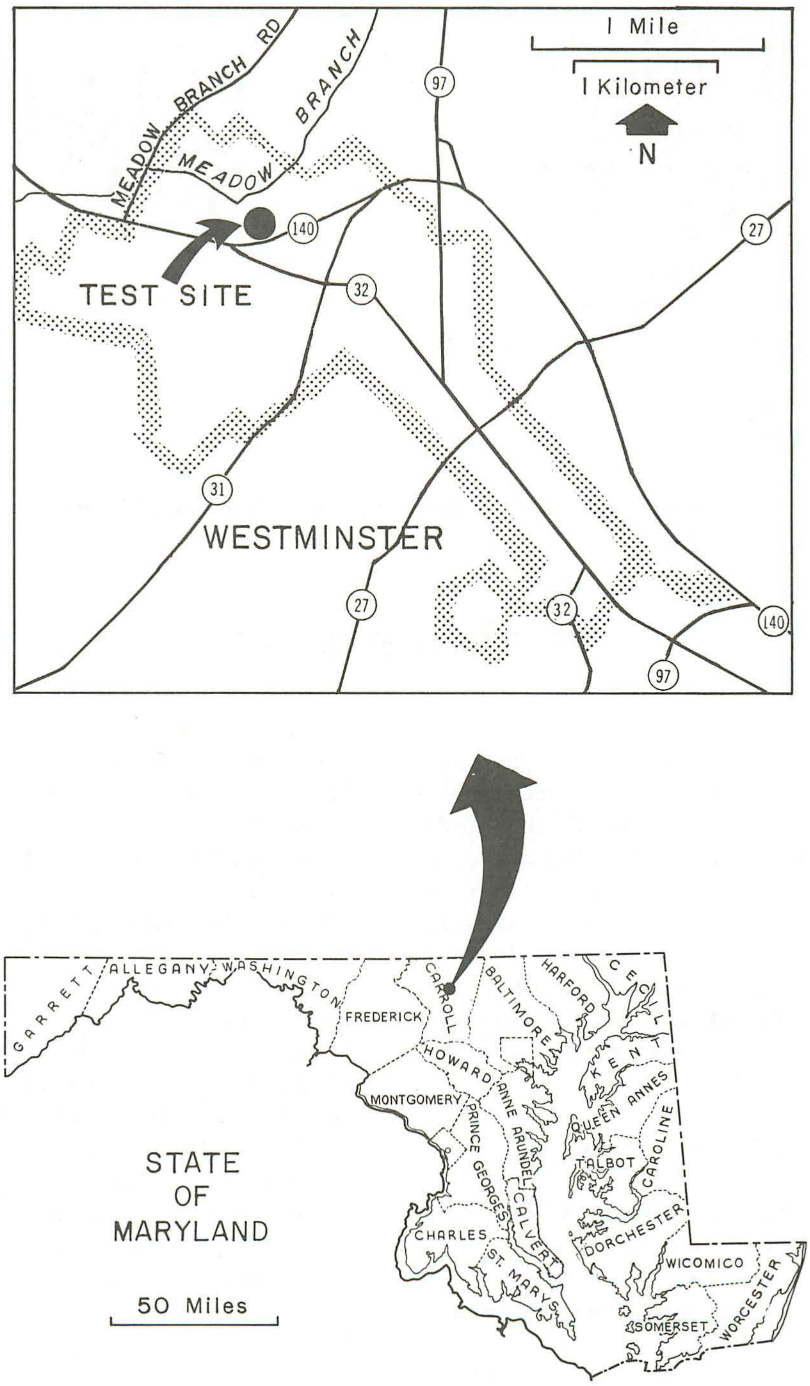
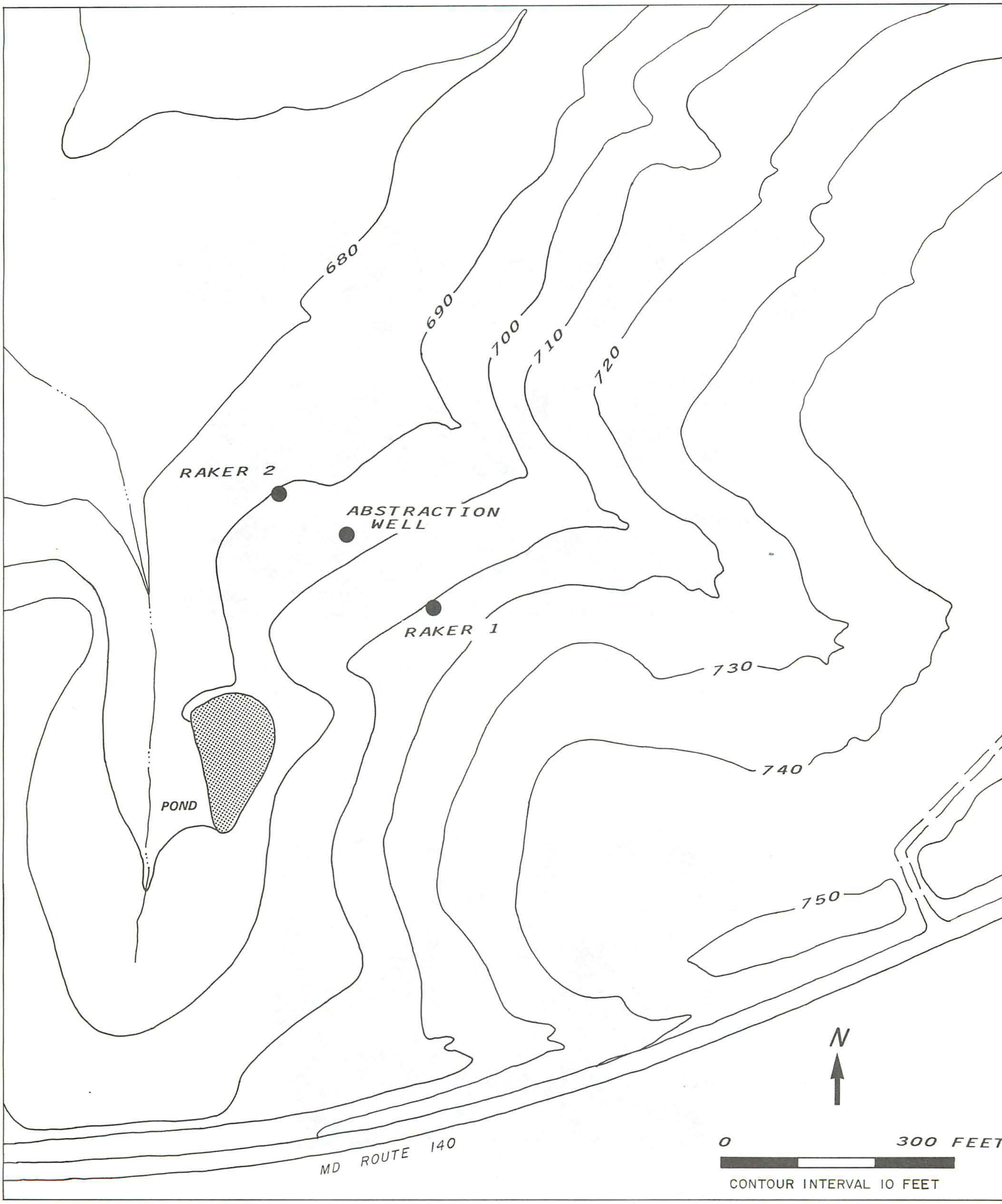


Figure 10.—Index maps showing location of the Westminster test well site.



Topographic contours from development plan supplied by City of Westminster.

Figure 11.—Westminster test well site.

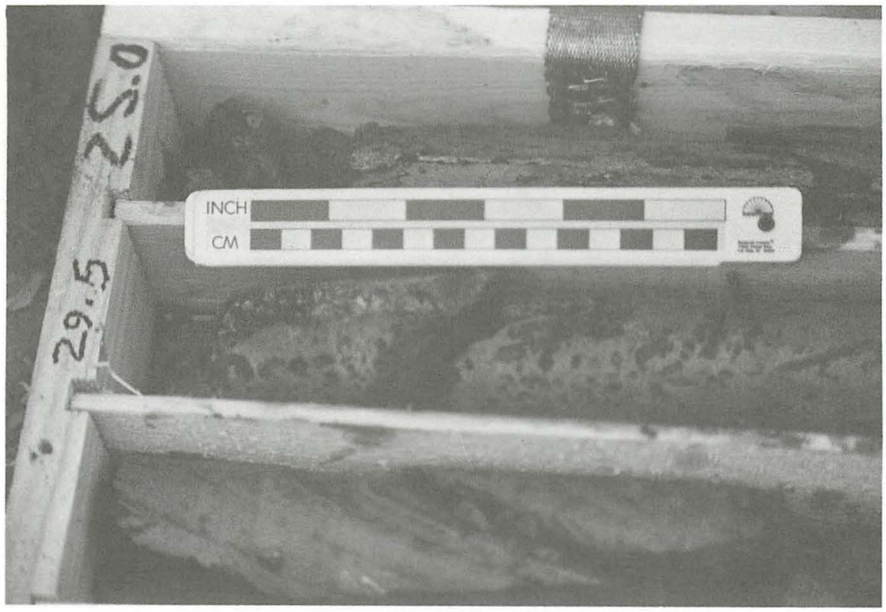


Figure 12.—Weathered metabasalt. The calcite that had filled amygdules has been removed by solution, enhancing porosity.

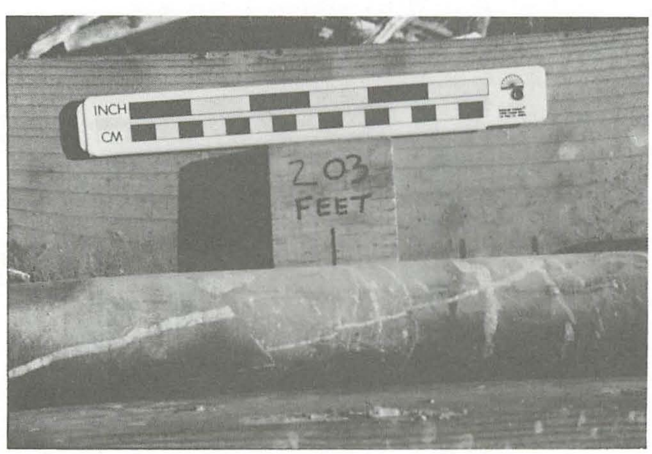


Figure 13.—Minor fault in test core at 203 feet.

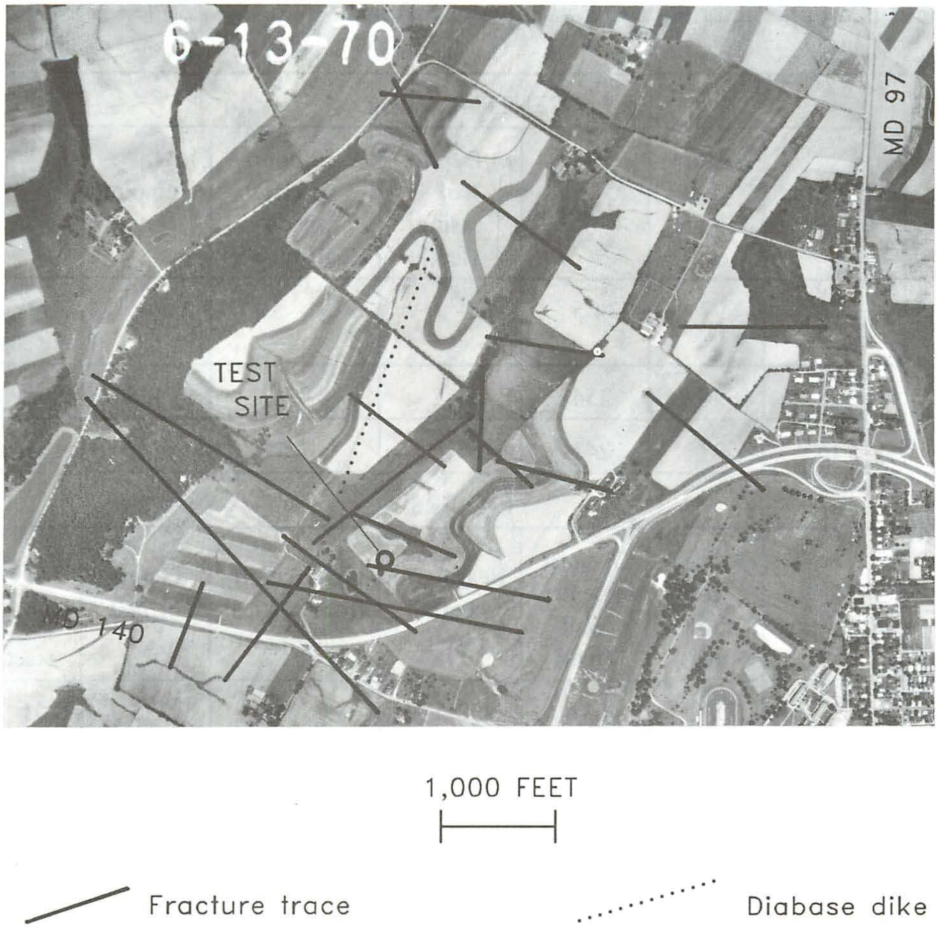


Figure 14.—Fracture traces in the vicinity of the Westminster test well site. Photography from USDA, Agricultural Stabilization and Conservation Service, flown 1970, scale 1:20,000.

vegetational differences, or similar features. The nearest fracture trace is about 60 ft from the test well; it may have had a significant effect on the flow of ground water to the well.

DESCRIPTION OF THE TEST HOLES

The test well (table 4) was constructed in a series of stages. The stages included vertical coring, overdrilling to 6-in. and 15-in. diameters, brushing and surging, hydraulic fracturing, and drilling rakers. Geophysical logging was carried out after each stage (table 5; fig. 15—see appendix) for three purposes: 1) To gain additional information regarding the geology of the site; 2) to identify zones where ground water entered the borehole; and 3) to detect hydraulically-significant changes in the borehole resulting from any of the yield-improvement efforts. Step-drawdown (variable-rate) pumping tests were conducted after six stages to evaluate the efficacy of that stage in improving yield. Two constant-rate pumping tests were run (one at the 6-in. diameter stage and one at the 15-in. diameter stage) to better identify hydrologic properties of the aquifer.

Construction began with the drilling of an N-series (approximately 3-in. diameter) corehole, from 24.8 ft (auger refusal) to 234.5 ft. The recovered core allowed more certain evaluation of fracturing and fracture surfaces. The material penetrated was chiefly phyllite, with some massive metabasalt and marble zones (fig. 16; see Appendix for detailed lithologic description of the core). Dissolution of several of the marble zones resulted in cavernous secondary permeability at three levels intersected by the corehole (at depths of 37–40.2 ft; 45.5–53.5 ft; and 58.7–59.5 ft). Geophysical and orientation logs were obtained from this hole (table 5). The caliper and other geophysical logs (fig. 15) do not show evidence of fractures; however, several are evident on the acoustic televiewer log (plate 1 and figs. 17 and 18).

After the initial corehole was logged, it was overdrilled to a diameter of approximately 6 in. This was accomplished by simply setting up the pneumatic rig over the hole and using the procedure for constructing a typical 6-in. hard-rock well. A suitably-sized bit with a leader for following the existing hole was not available; however, the acoustic televiewer log shows

Table 4.—Construction characteristics of Westminster test well

CENTRAL WELL							
Inventory no.	Diameter (inches)	Altitude (feet above msl)	Depth drilled (feet)	Depth of casing (feet)	12-hour specific capacity [(gal/min)/ft]	Pumping rate	Remarks
CL Bd 176	3	697	234.5	--	--	--	Exploratory corehole
CL Bd 175	6	697	254	54	8.7	168	Abstraction well
	15	697	241	55	7.5	248	Abstraction well

RAKERS								
Inventory no.	Diameter (inches)	Altitude (feet above msl)	Distance to central well (feet)	Bearing to central well	Inclination from vertical (degrees)	Length drilled (feet)	Length of casing (feet)	Remarks
CL Bd 177	3	711	144	N52.5°W	45	228.5	61	Uphill raker
CL Bd 178	3	690	104	S51°E	37	191	31	Downhill raker

Table 5.—Geophysical logs obtained from the test holes

Log type	3-inch hole CL Bd 176	6-inch hole CL Bd 175		15-inch hole after development CL Bd 175
		as drilled	after development	
Hole orientation	x	-	-	x
Caliper	x	x	x	x
Spontaneous potential	x	-	-	-
Resistivity	x	-	-	-
Resistance	x	-	-	-
Natural gamma	x	-	-	-
Gamma-gamma	-	x	x	x
Neutron	x	x	x	x
Acoustic velocity	-	x	x	x
Acoustic televiewer	x	x	x	x

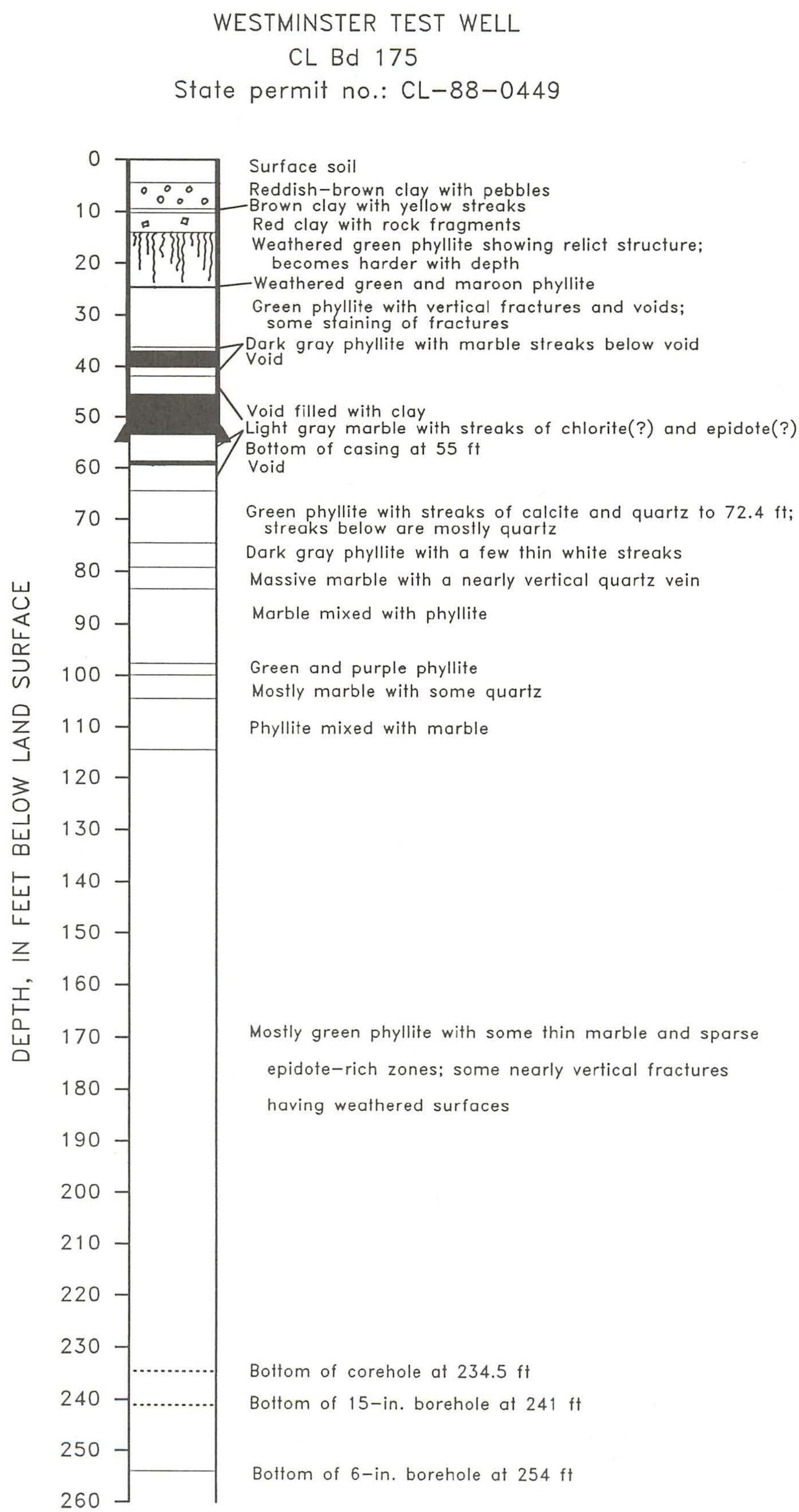


Figure 16.—Geologic log of the Westminster test well.

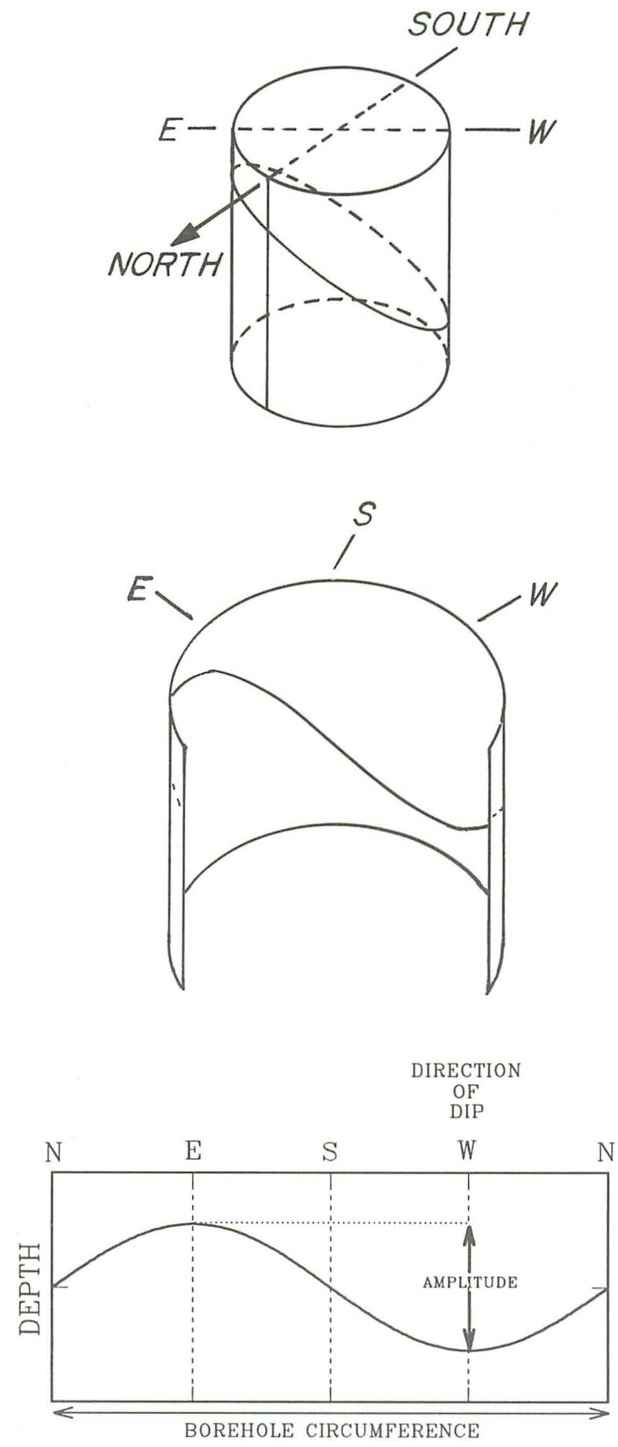
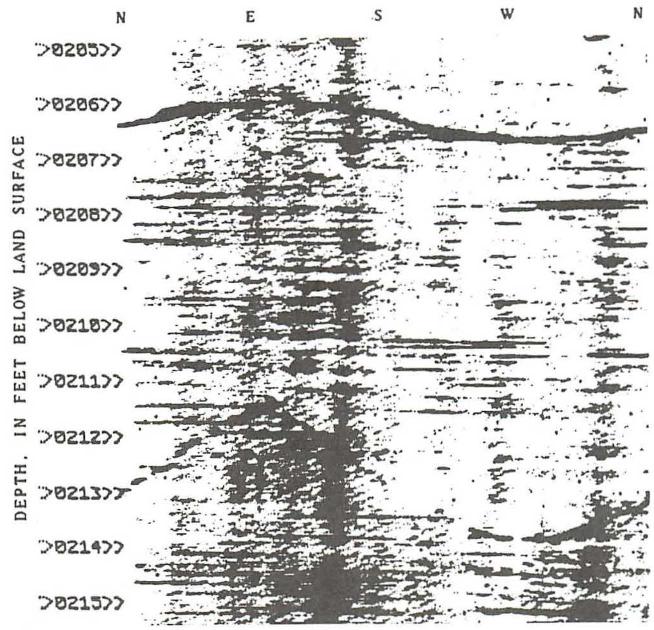


Figure 17.—How the acoustic televiewer log is interpreted. The tool contains a transmitter and a receiver that spin around an axis parallel to the borehole axis. A magnetic compass is used to orient the acoustic signals echoing off the borehole wall and returning to the receiver. A void, rough spot, or other region where the borehole wall is not perpendicular to the tool will cause the signal to bounce off in another direction and not be received at the tool, resulting in a dark spot. The graphic log may be thought of as a sheet wrapped around the borehole cylinder that has been slit vertically and unwrapped. A dipping planar fracture shows as a sinusoidal curve in this projection. The dip of the plane is in the direction of the lowest point along this curve; the amount of dip is the arctangent of (amplitude/borehole diameter).



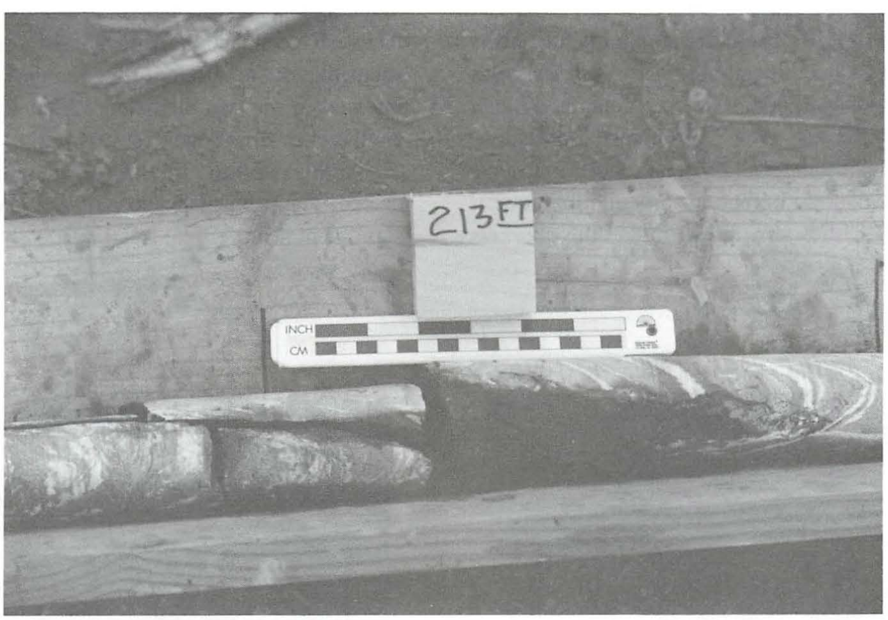


Figure 18.—Portion of acoustic televiewer log (top) and photograph of core (bottom) showing fracture at a depth of approximately 213 feet. The reddish stain on the fracture surface indicates that this was a naturally-occurring fracture, not one that was induced by drilling. The log confirms that the fracture extends into the formation.

that a fairly good coincidence was obtained. A trace of the smaller corehole can be seen protruding somewhat in the wall of the 6-in. borehole wall (pl. 1). The caliper log for the undeveloped 6-in. hole shows a portion of the nonconcentric 3-in. hole in the side of the 6-in. hole; the neutron log shows essentially the same features as shown by the neutron log for the 3-in. hole (fig. 15). Kicks on the acoustic velocity log (fig. 15) at depths of about 89, 116, and 204 ft may be due to tight fractures; there are no corresponding features on any of the other logs.

A step-drawdown test was conducted on the well at this time to establish the initial productivity of the well. After the test, the well was developed by wire brushing for 4 hours followed by surging for 4 hours. (The wire brushes and surge block are shown in figure 19.) Another step-drawdown test was conducted to evaluate the effectiveness of brushing and surging.

The well was then stimulated by hydraulic fracturing. A single mechanical packer was used, set initially at a depth of 73 ft, and subsequently set at depths of 139, 158, and 198 ft. A total of 19,338 gal of water was injected in less than 3.5 hours, at rates ranging from about 75 to 125 gal/min. Pressures ranged from about 200 to 1,000 psi. No propping agent was used.

Geophysical logs were run again after hydraulic fracturing. The caliper log (fig. 15) differs from the previous version mainly in having picked up some additional length of the off-center 3-in. hole protruding from the borehole wall (the caliper tool has three thin fingers and therefore can easily miss a feature that is not present around most of the borehole circumference). The caliper log also shows slight enlargement of small cracks at depths of about 204 and 213 ft. The gamma-gamma log shows a decrease in density at a depth of about 94 to 98 ft that was not evident on the previous version. The core contained much marble at this zone, so the log, which is somewhat direction-sensitive (it is pressed against the wall of the borehole) may have detected a void just beyond the borehole (direction unknown). The acoustic velocity log shows more kicks than the previous version, suggesting that hydraulic fracturing may have opened up some fractures. No new significant features can be seen on the acoustic televiewer log.

The following day a step-drawdown test was done to judge the effectiveness of the hydraulic fracturing. A 12-hour constant-rate pumping test followed by 12 hours of recovery measurements was conducted after the step-drawdown test to evaluate aquifer properties as well as performance of the well.

The well was enlarged again, this time to a nominal diameter of 15 in. Drilling a hole this size requires a particularly large bit and equipment to handle it (fig. 20), which adds to the cost of the well. Traces of the 6-in. hole as well as the 3-in. hole can be seen in the acoustic televiewer log (fig. 21), indicating that the original course was followed approximately. Eighteen-inch steel casing was cemented in place to a depth of 55 ft. The well was developed by 4 hours each of brushing and surging, and another suite of geophysical logs was run.

The caliper log (fig. 15) shows a somewhat rougher hole than the 6-in. borehole was, but otherwise no significant features. The gamma-gamma log does not show the same density decrease at about 94 to 98 ft; it could be a difference in tool orientation from the previous run, or it may indicate that the suspected void was breached by the larger bit. Supporting the latter contention is the fact that the neutron log for the 15-in. hole does not show the porosity increase for that zone that the logs for the smaller-diameter holes show. A very large decrease in acoustic velocity is shown for this zone, which also may indicate a breach in the rock separating the void from the borehole. It is possible that such a connection made by the larger borehole could be responsible for the different flow regimes observed during pumping tests at the two diameters. After the hole was logged, yet another step-drawdown test was run.

At this point the first of two inclined holes, or rakers, was drilled. The primary purpose of the rakers was to intercept any significant near-vertical fractures that might be present and im-

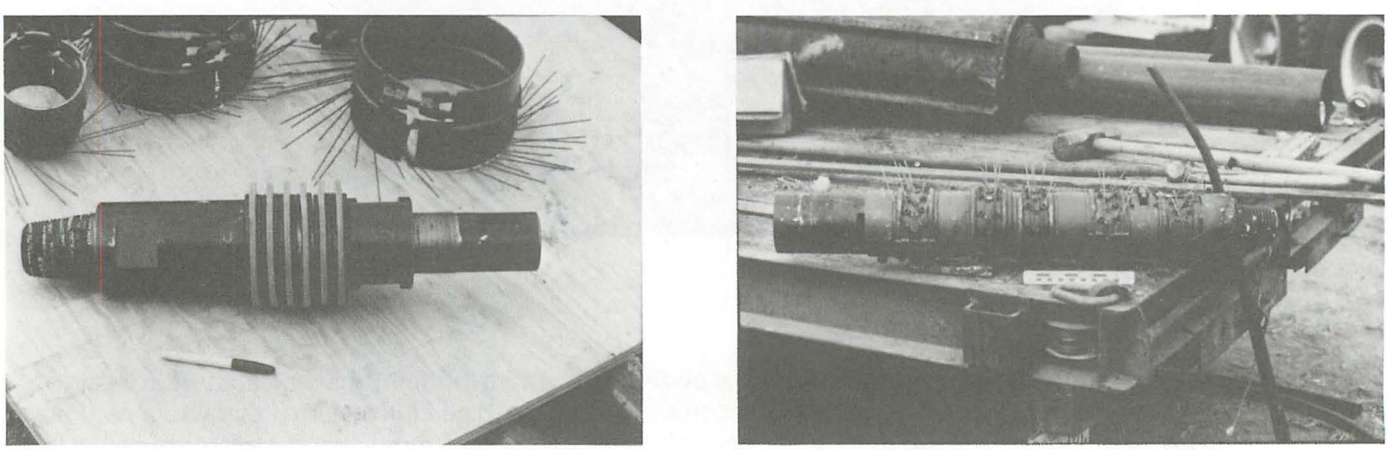


Figure 19.—Wire brushes and surge blocks used for developing test well (left photo). The wire brushes are strung together on a sub-assembly (shown in right photo after use).

Figure 20.—Photograph showing the 15-inch bit and stabilizer assembly.

prove their hydraulic connection to the central well. Additionally, each raker would add to the effective diameter of the well; Day et al. (1978) modelled this effect in a sand tank. A track-mounted coring rig was used to drill an NX corehole from a site located 144 ft southeast from the central, large-diameter well (fig. 22). The corehole was begun with an inclination of 45 degrees and aimed to hit the central well (allowing for driller's windage, or intuitive estimation of drift of the hole). The corehole came to within about 20 ft of the central well (fig. 23). To help determine whether it linked any significant water-bearing fractures to the vicinity of the central well, a step-drawdown test was conducted.

A second raker was drilled 104 ft northwest (downhill) of the central well at an inclination of 37 degrees from the vertical. Bearing and inclination at discrete intervals in each hole were obtained from borehole surveys (the logging device operated by photographing the projection of the axis of the long tool onto an oriented, horizontal compass card within the tool) (table 6).

Figure 22.—Drilling the uphill raker.

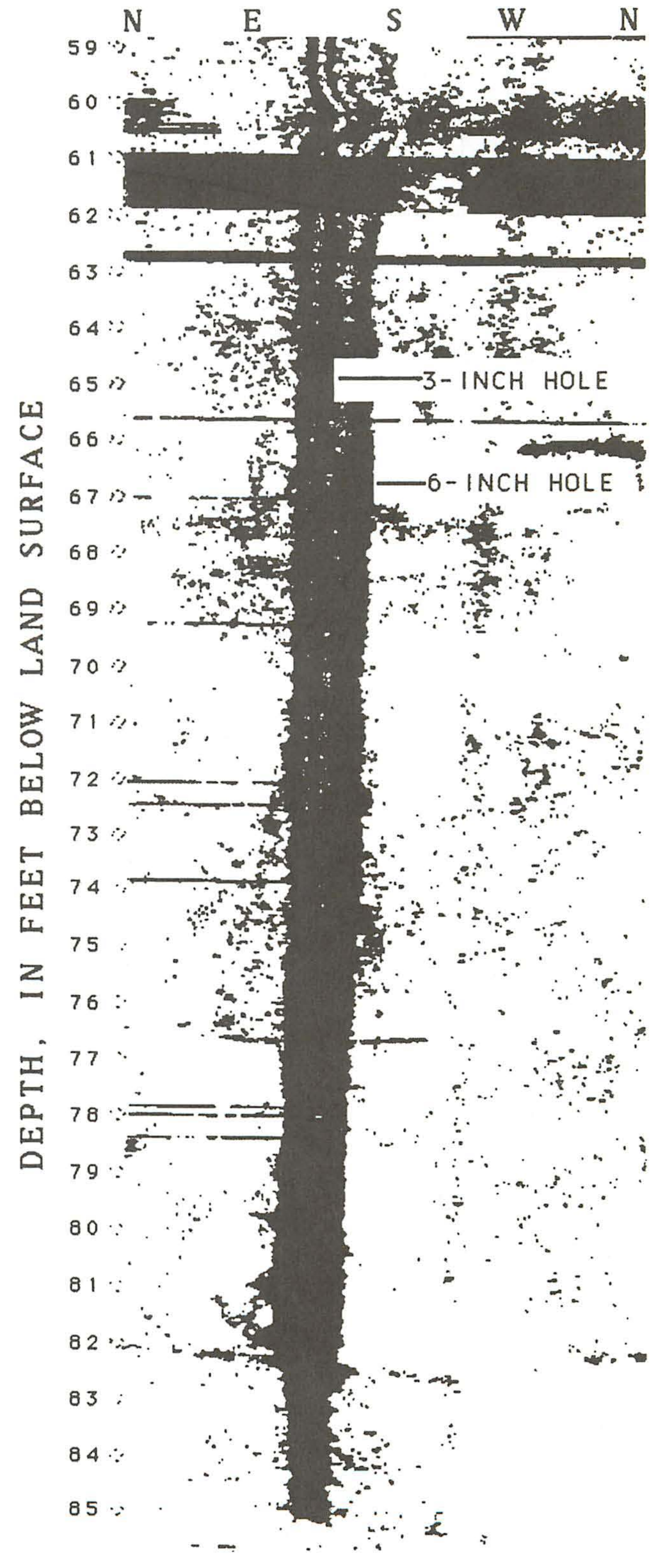


Figure 21.—Portion of acoustic televiewer log showing traces of nonconcentric 6-inch and 3-inch holes in the wall of the 15-inch hole.

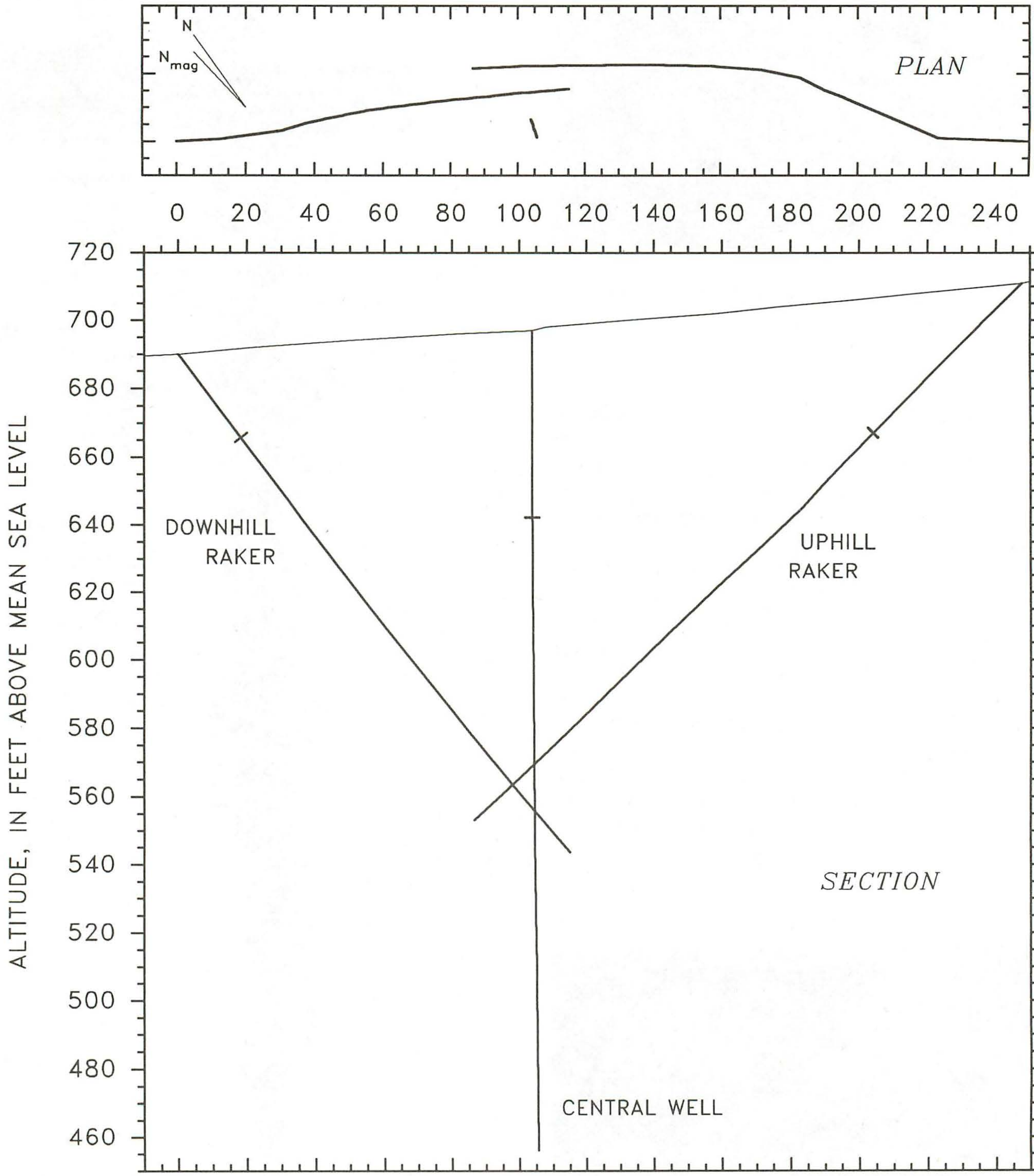


Figure 23.—Plan and section showing the central well and rakers. Short transverse lines indicate the lower ends of casings.

Table 6.—Borehole survey results

[Magnetic declination is 7.5° west]

CL Bd 175 Central hole (15-inch) Cased to 55 feet		
Apparent depth (feet)	Bearing (magnetic)	Inclination (degrees from vertical)
0	--	0.0
85	S20°W	1.4
105	S26°W	1.5
125	S25°W	1.4
145	S24°W	1.4
165	S18°W	1.7
185	S25°W	1.8
CL Bd 176 Uphill raker Cased to 61 feet		
Apparent depth (feet)	Bearing (magnetic)	Inclination (degrees from vertical)
0	N45°W	45
70	N24°W	47
80	N25°W	45
90	N20°W	45
100	N35°W	47
120	N43°W	47
140	N46°W	46
160	N48°W	46
170	N48°W	46
180	N48°W	46
190	N48°W	46
200	N49°W	47
220	N50°W	48

CL Bd 177 Downhill raker Cased to 31 feet		
Apparent depth (feet)	Bearing (magnetic)	Inclination (degrees from vertical)
0	S51°E	37
17	Inside rod	37
47	S56°E	37
57	S65°E	37.5
67	S60°E	37.5
77	S59°E	37.5
87	S59°E	38
97	S56°E	38
107	S55°E	38.5
117	S54°E	39
127	S54°E	39.5
137	S54°E	39.5
147	S53°E	40
157	S54°E	40
167	S52°E	40.5
177	S52°E	41
178	Inside rod	41
187	S51°E	41

This raker apparently came within about 10 ft of the central well (fig. 23). Another step-drawdown test was conducted after completion of the second raker.

RESULTS OF BOREHOLE YIELD AND AQUIFER TESTING

Two constant-rate pumping tests were conducted for evaluation of aquifer properties and to determine the presence of any nearby hydrologic boundaries. Step-drawdown pumping tests were conducted after each construction and development procedure in order to test the efficacy of that procedure.

Constant-Rate Tests

Test of 6-inch well

After all development and stimulation, the 6-in. well was pumped at a nearly constant rate of about 168 gal/min for 12 hours. Water levels in the well were measured during this period, and for an additional 12-hour recovery period. The measurements were made using an electric sounding tape lowered within a 1-in. polyethylene pipe installed in the well to isolate the sounding probe from splashing water. The constant-rate test began the same day that the preceding step test was conducted (test 3). Recovery from test 3 was incomplete, there remaining over 1 ft of residual drawdown. Consequently, residual drawdown was extrapolated and water levels for the constant-rate test were adjusted by superposition. The specific capacity after 12 hours of pumping at this rate was 8.7 (gal/min)/ft.

A full-logarithmic plot of adjusted drawdown versus time shows deviations from the Theis solution at both early and late times (fig. 24). The deviation for time less than 1.5 min is due to delayed gravity response in the unconfined aquifer. Drawdowns for times between about 2 and 200 minutes lie along the Theis curve for late drawdowns, and drawdowns for later times show the effect of an impermeable boundary (also detected by test 3). Most of the intervening points lie along the Theis curve, and because there were no observation wells (to permit calculation of specific yield and storage coefficient) a simple Theis curve would have sufficed for matching the data. However, in recognition of the unconfined nature of the aquifer and to see the magnitude of deviation from the Theis solution at early time, the type-curve method of Neuman (1975) showing delayed gravity response was applied to figure 24. The data were matched with individually-plotted type B curves having different values of β until a match was found, which was on a curve for $\beta = 0.1$. Drawdown corresponding to a match point at (1,1) is 1.9 ft. Transmissivity may thus be estimated by

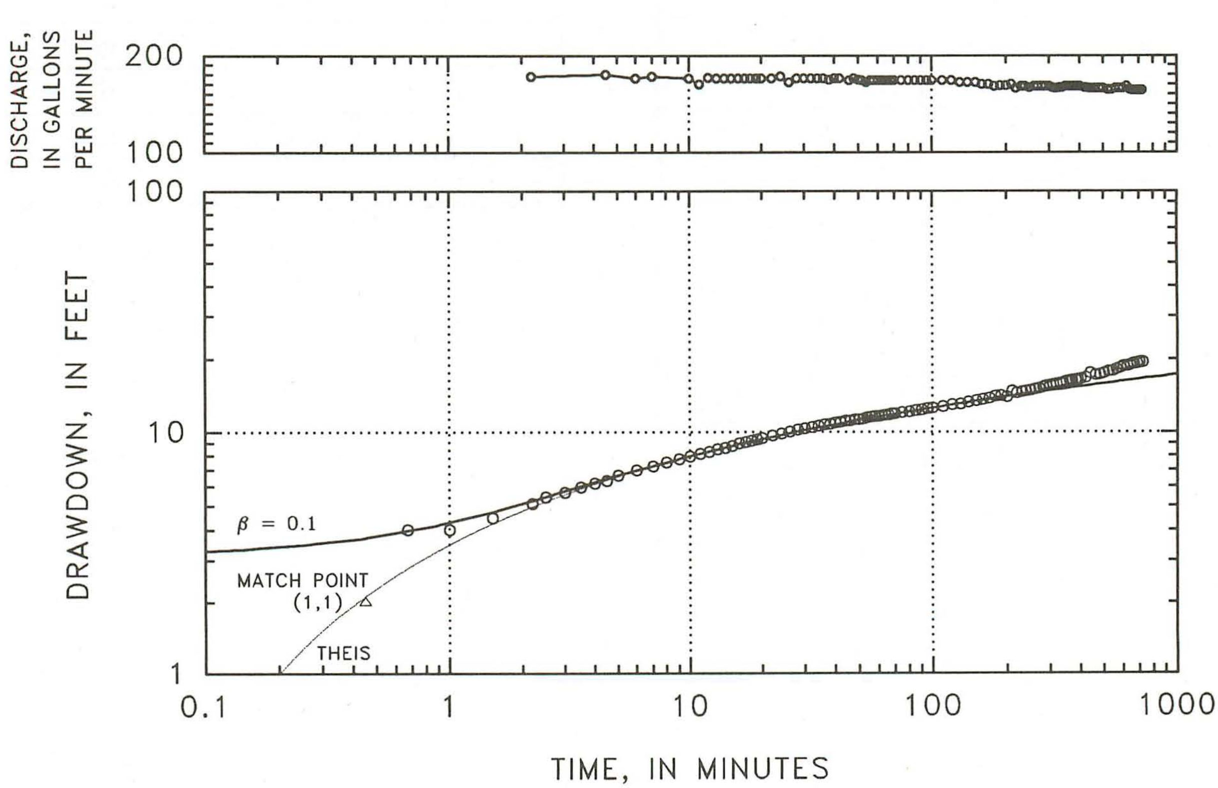


Figure 24.—Full-logarithmic plot of adjusted drawdown versus time, 12-hour constant-rate pumping test of 6-inch well.

$$
\begin{aligned}
T &= (15.32\ \mathrm{ft^3 gal^{-1} min \cdot d^{-1}})(Qs_D/s) \\
&= (15.32\ \mathrm{ft^3 gal^{-1} min \cdot d^{-1}}) \\
&\quad [(174\ \mathrm{gal \cdot min^{-1}})(1/1.9\ \mathrm{ft^{-1}})] \\
&= 1{,}403 \approx 1{,}400\ \mathrm{ft^2/d}.
\end{aligned}
$$

where T is transmissivity, in ft²/d; Q is discharge, in gal/min; s_D is dimensionless drawdown from the type curve; and s is observed drawdown, in ft. The constant, 15.32, includes the conversion factors needed for the measurement units used.

A semi-logarithmic plot of the adjusted data (fig. 25) more clearly shows the effects of the impermeable boundary at about 200 min of pumping. If the storage coefficient was known, the distance to this boundary could be estimated (Strausberg, 1967), although aquifer heterogeneities would add to the uncertainty of the estimate. Transmissivity can be estimated using the first limb of the plot:

$$T = 35.3\ \frac{Q}{\Delta s}$$

where Q is in gal/min, Δs is in feet, and the constant 35.3 incorporates the conversion factors necessary to give T in ft²/d.

$$T = 35.3\ \frac{174}{4.4}$$

$$T = 1{,}396 \approx 1{,}400\ \mathrm{ft^2/d}$$

Recovery was measured for 12 hours after the pump was turned off (fig. 26). The earliest recovery measurements (beginning at the right-hand side of the graph) show the delayed gravity response and then approach the late Theis behavior at t/t′ (time since pumping began/time since pumping ended) of about 65. The impermeable boundary is evidenced at t/t′ of about 10. About 2.8 ft of residual drawdown remain at t/t′ = 1, providing further evidence of the limited extent of the aquifer. Transmissivity estimated from the late response is 1,320 ft²/d. The changes in slope of the recovery graph do not fall at exactly the same times as the corresponding changes of the drawdown graph (fig. 25). That is to say, for instance, that the initiation of

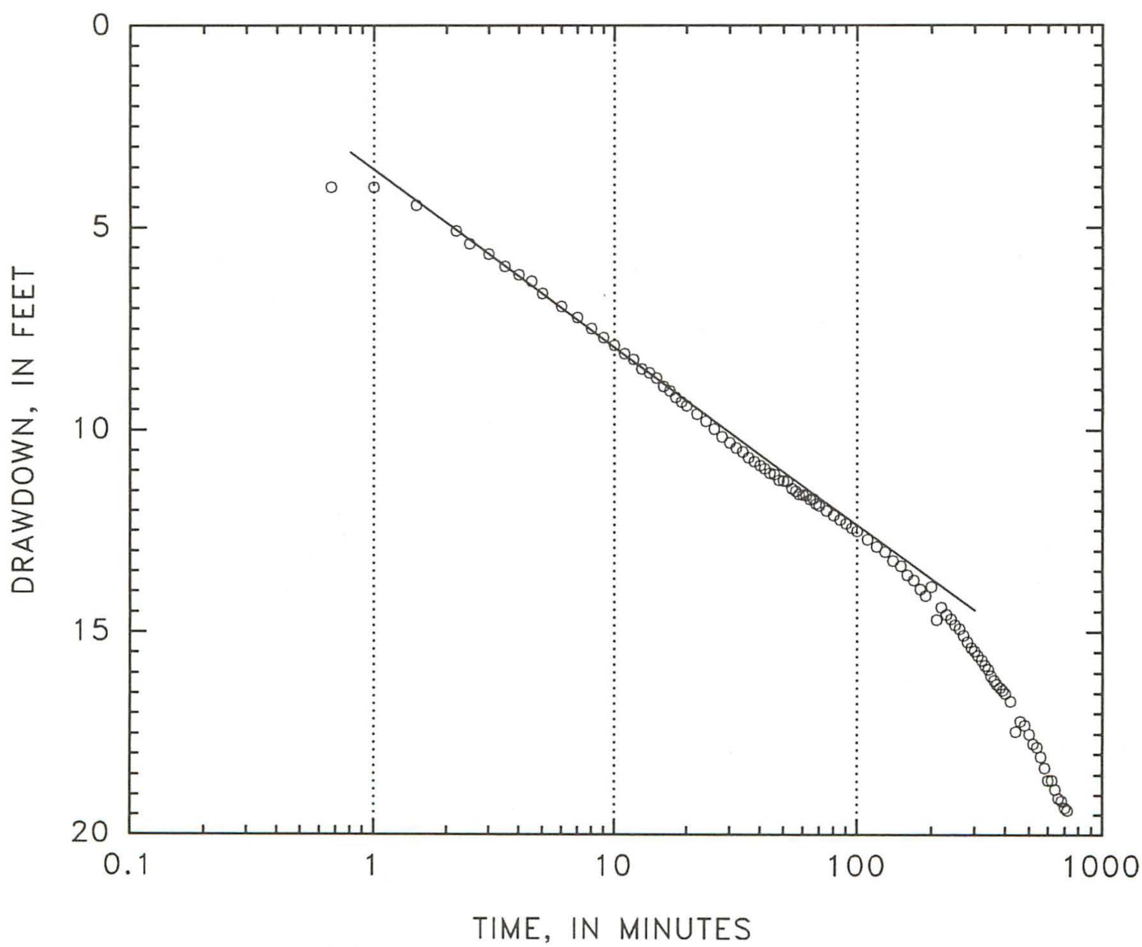


Figure 25.—Semi-logarithmic plot of drawdown versus time, 12-hour constant-rate pumping test of 6-inch well.

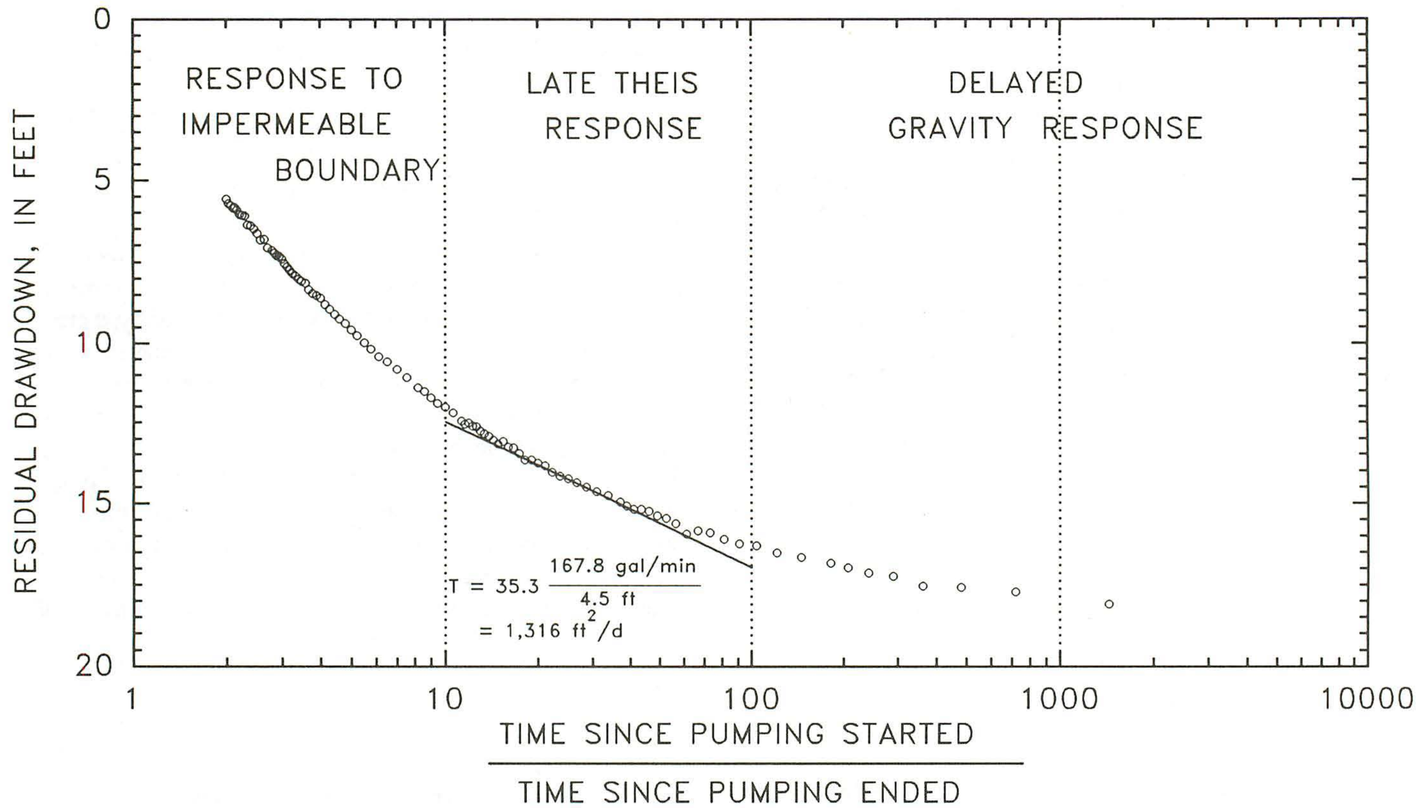


Figure 26.—Recovery after 12-hour pumping test of 6-inch well.

the late Theis response occurred after about 9 min of recovery compared to about 2 min after pumping began. This may be attributable to vertical heterogeneity of aquifer storage coefficient S and specific yield S_y—at early times elastic storage for the saturated thickness at the well differs for recovery compared to pumping because the water table at the end of pumping was lowered below the overburden and the highly weathered zone.

Test of 15-inch well

A final, 24-hour test was conducted with the large-diameter well (test 8). Pumping began at a rate of 248 gal/min (fig. 27), but this rate could not be maintained after about 1,000 min and dropped down to about 160 gal/min. Water levels were measured in the abstraction well as before. The specific capacity after 12 hours of pumping was 6.9 (gal/min)/ft and after 24 hours of pumping was 5.2 (gal/min)/ft. The results of this test are considerably different than the results of the 12-hour test (fig. 28), and cannot be explained simply by the larger well diameter. The primary mode of ground-water flow for the first 400 to 500 min seems to be linear flow, because the slope of the time-drawdown curve is nearly equal to 0.5 on the full logarithmic plot (fig. 27); also, this segment of the curve is linear in an arithmetic plot of drawdown against the square root of time (fig. 29). At later time the slope steepens to 1 (on the log-log plot), indicative of pseudo-steady state conditions, i.e., in this finite aquifer, drawdown everywhere increases linearly with time. Such drawdown behavior may be due to dewatering of the upper voids, which were cased off. After about 1,000 min the pumping rate decreased noticeably, and some difficulty was experienced in obtaining a sufficient, constant rate. It appears that the water level in the abstraction well fell to a position near the intake of the pump, which was not set as deep as it was in earlier tests.

Water levels were also measured in the two rakers, one located 144 ft uphill from the pumping well, and one located 104 ft downhill (fig. 27). The inclinations of the rakers complicate interpretations of their responses to pumping—water levels in these boreholes represent an integration of head along the open borehole, which is not parallel to any equipotential lines as required by the analytical assumption of horizontal flow. Water-level measurements in the rakers were converted to a vertical reference, but it must be kept in mind that such vertical distances do not represent head values at any single location; and as the water level in a raker declined, the average distance from the open borehole to the pumping well also decreased. On the other hand, the assumption of a vertical observation well in a horizontal flow field may be less important in a fractured-rock setting such as this one where void geometry results in linear flow and vertical flow components. The response of the uphill raker seems to show an initial (after less than 3 min of pumping) borehole dewatering followed by conversion to linear flow, until some time after 500 min, when the water level apparently dropped below the permeable zone connecting the two boreholes.

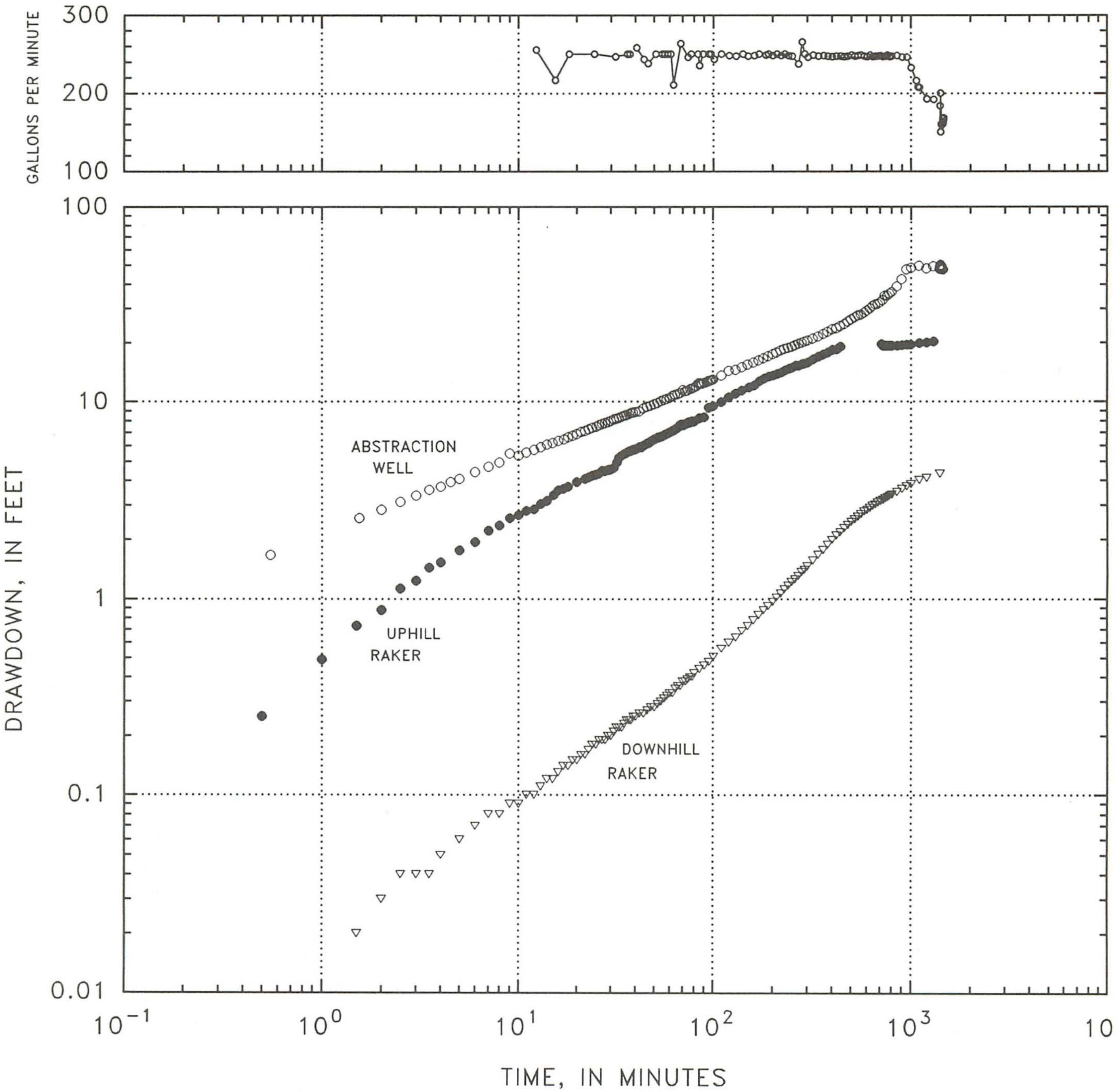


Figure 27.—Full-logarithmic plot of drawdown versus time, 24-hour constant-rate pumping test of 15-inch well. Drawdowns in the rakers refer to vertical distance calculated from measurements made along borehole.

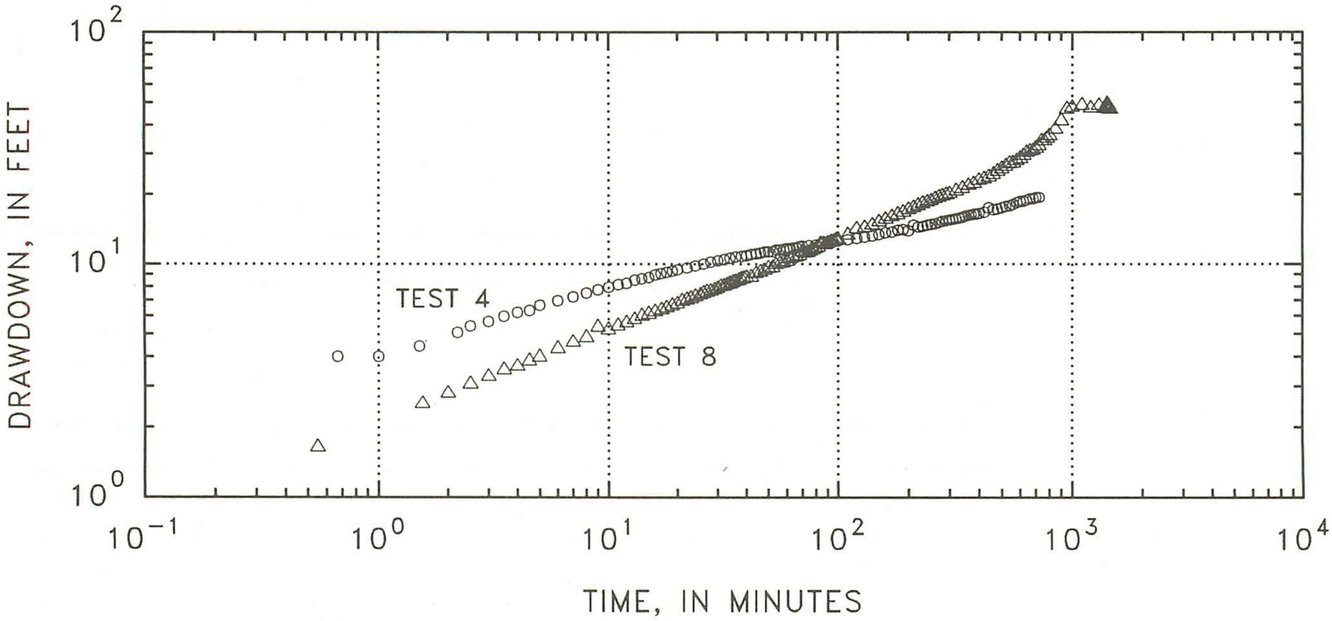


Figure 28.—Drawdown versus time for both constant-rate pumping tests. The average pumping rate for test 4 (6-inch well) was 168 gal/min; the pumping rate for test 8 (15-inch well) averaged 229 gal/min. There appears to be a fundamental difference between the two tests in drawdown behavior.

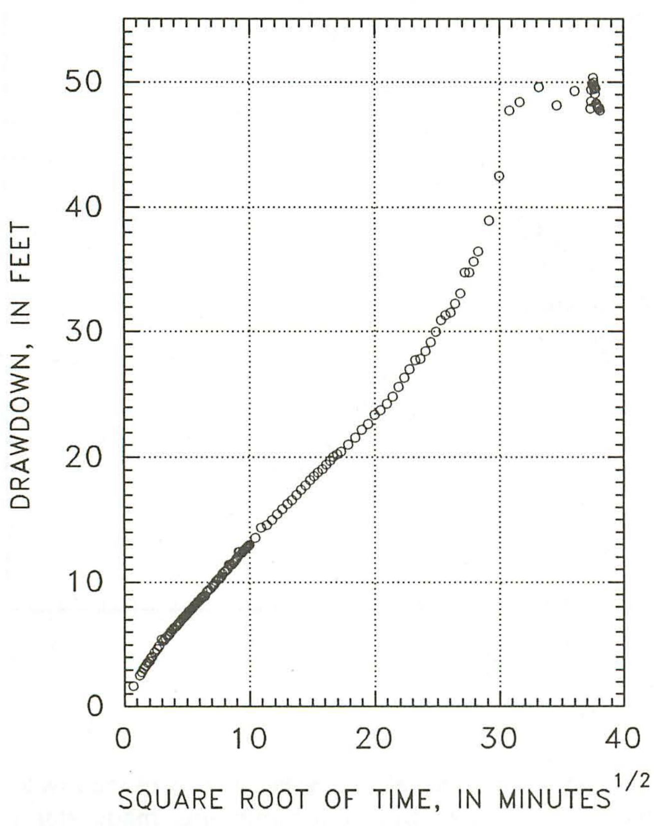


Figure 29.—Drawdown plotted against the square root of time, 24-hour constant-rate pumping test of 15-inch well.

Water level declined far more in the uphill raker than in the downhill raker (fig. 27). A composite drawdown response curve (fig. 30) can be constructed using data from both rakers (Jacob, 1950, p. 368) by plotting drawdown against $\log(r_i^2/t_i)$, where r_i is the distance of observation well i from the abstraction well and t_i is time since pumping began to when drawdown was measured in the raker. It is not clear in the present case what values to assign to r_i because of the inclination of each raker; both approach to about 10 to 20 ft of the central well. Therefore, an arbitrary unit value was assigned to r_1. Multiplying the values of 1/t for the downhill raker by 60 shifts the position of that curve enough to superimpose it on the curve for the uphill raker. Thus we may infer that the effective distance from the downhill raker to the abstraction well is almost 8 times the distance from the uphill raker to the abstraction well (the square root of 60). The average distances of each raker to the abstraction well are similar; however, the effective distances may be controlled by the locations and geometries of the voids, particularly with respect to how their vertical distribution relates to the proximity of the rakers. Alternatively, much of the region penetrated by the uphill raker consists of weathered rock, which would seem to be considerably more permeable than the unweathered rock in the vicinity of the downhill raker.

Recovery after the 24-hour pumping test behaved oddly (fig. 31) but yields some information regarding hydrologic conditions in the vicinity of the well. Residual drawdowns measured in the abstraction well fall along a curve (with a slight hump in it), due to linear flow conditions. Water levels measured in the uphill raker held steady for about 300 min after pumping stopped, and then began to rise apace. Water level in the down-

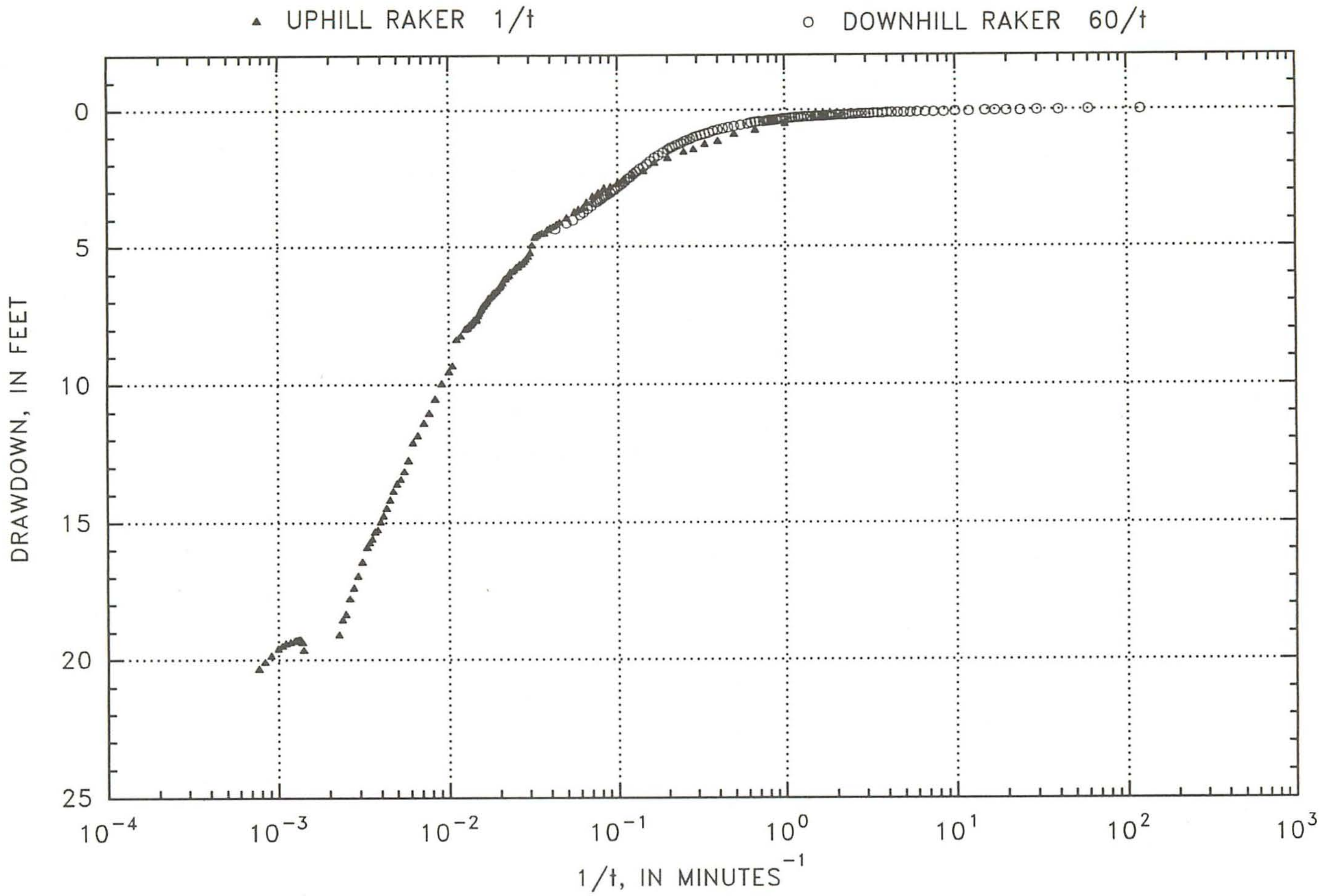


Figure 30.—Composite drawdown curve for both rakers, 24-hour constant-rate pumping test of 15-inch well. The curves were superimposed by multiplying the values of 1/t of the downhill raker by 60, which suggests that the effective distance of this borehole from the abstraction well is square root (60), or almost 8, times that of the uphill raker.

hill raker continued to decline; after more than 400 min the rate of decline decreased as the effects of recharge began to be felt.

Aquifer coefficients cannot be estimated from the recovery data, but these data can be used in conjunction with data from the abstraction phase to gain some insight into how the aquifer yields water to the well. The central well intersects three significant voids (the upper two are cased off) which effectively extend the borehole dimensions and alter its geometry so that groundwater flow in the vicinity of the well is linear, rather than radial. Although cased off and not providing direct entry of water into the well, the two upper voids (coupled with fractures and the third void that does open to the borehole) act as conduits leading water toward the well. Although both the 6-in. and the 15-in. holes passed through the same sequence of rock and structure, the larger hole may have established a better connection with the fractures. For example, the acoustic televiewer log for the 15-in. hole (plate 1) shows a fracture at about 214 ft depth open as much as 0.5 ft, whereas the same fracture was only open about 0.2 ft to the 6-in. well. Unfortunately, borehole flow information is not available to determine how much, if any, inflow is provided through this fracture. The hydraulic connections between both rakers and the abstraction well are probably shallow, primarily within the overburden and weathered rock zone (fig. 32). The water-level decline in the downhill raker indicates dewatering in the vicinity of the raker. After the pump was shut off, water level in this raker continued to decline slightly, as ground water drained from this region to the abstraction well. The small magnitude of water-level changes in the raker probably were due to the low permeability of the unweathered rock into which this water drained.

The hydraulic connection between the abstraction well and the uphill raker is somewhat better, as evidenced by the similarity of drawdown curves (fig. 27). That similarity disappears after a time of about 500 min, at which the rate of drawdown abruptly decreased in the raker but not in the abstraction well. Difficulties in making measurements in the raker precluded obtaining data to define water-level behavior during a period of 271 min, during which some oscillation apparently occurred. The

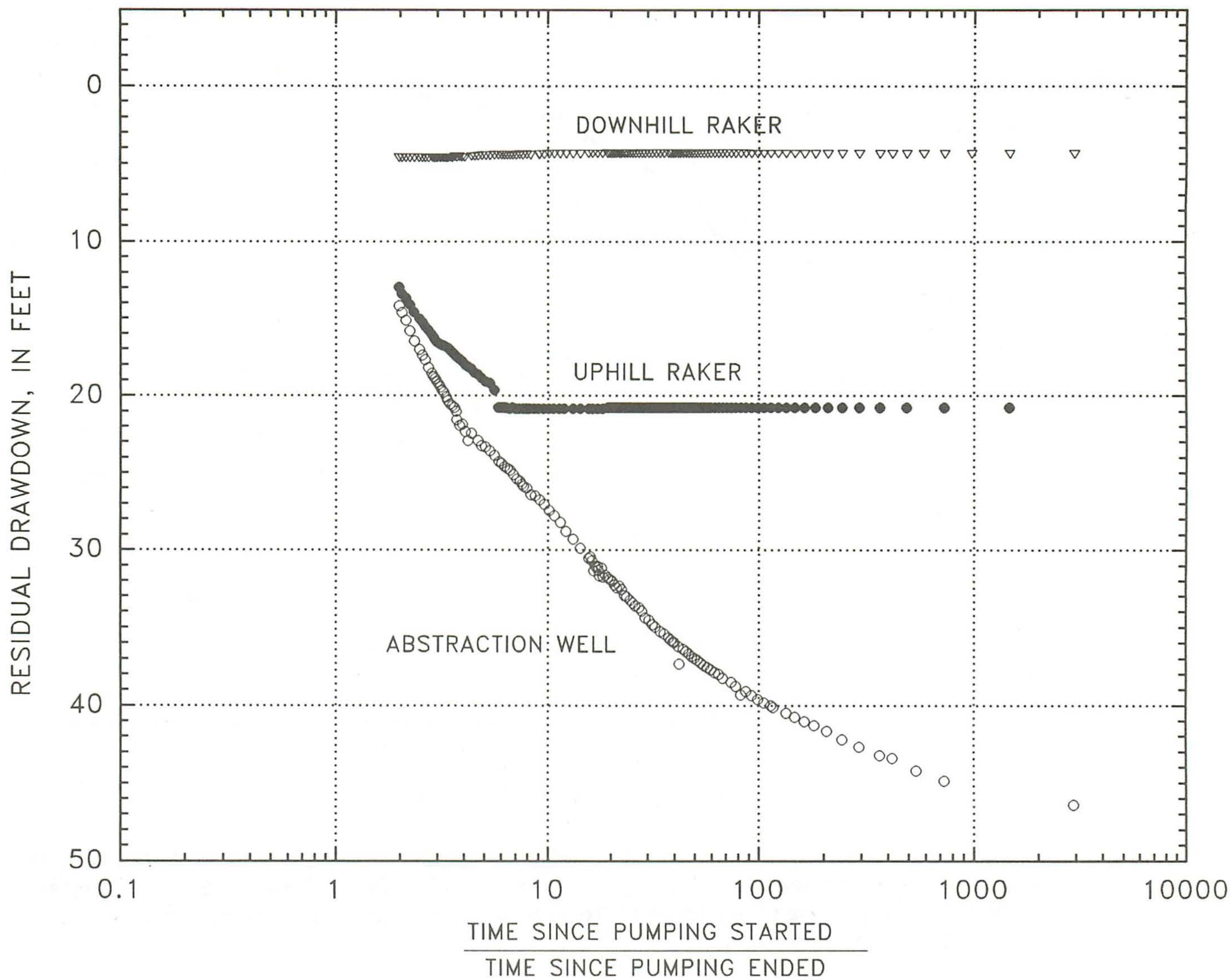


Figure 31.—Recovery phase of 24-hour constant-rate pumping test of 15-inch well. The abstraction well was pumped for 1,460 minutes at an average of 229 gallons per minute and recovery was measured for 1,500 minutes after the pump was shut off.

dramatic decrease in the rate of drawdown in the uphill raker occurred as the water level measured in the abstraction well fell below the level of the upper two voids. The drawdown response of the abstraction well steepened during this period—changing over from a linear-flow mode to pseudo-steady state (dewatering of the voids). The weakening of the abstraction well-uphill raker connection at this time suggests that ground-water flow between the two boreholes is predominantly in shallow weathered rock via the voids, which may connect directly to the weathered rock or indirectly through a short zone of fractured but unweathered rock (fig. 32).

Recovery in the uphill raker supports the foregoing hypothesized flow system. The water level was drawn down below the level of the weathered rock-voids connection, so after pumping ceased the water level in the raker remained unchanged until the rising water level restored the connection, after which recovery in the raker commenced.

Step-Drawdown Pumping Tests

C.E. Jacob (1947) presented a method to evaluate the linear and nonlinear components of head loss based on drawdown measured in an artesian well pumped at different rates during intervals of equal periods, or steps. Jacob's equation summarizing this analysis is

$$s = BQ + CQ^2$$

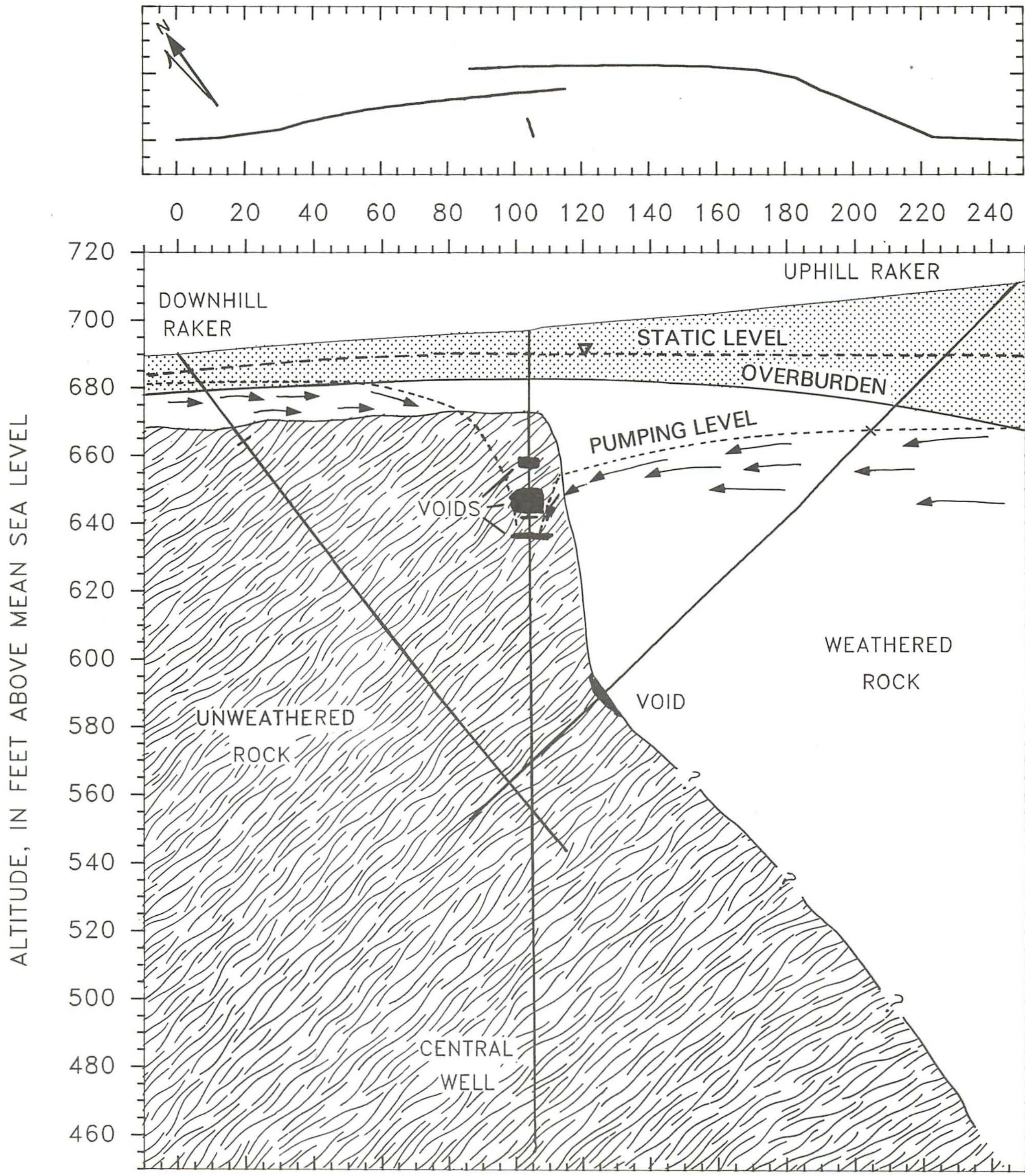


Figure 32.—Schematic of aquifer in the vicinity of the test well. Schistosity generally dips toward the northwest (to the left in the section). Arrows indicate ground-water flow; bottoms of casings are shown by short transverse lines.

Table 7.—Summary of step-drawdown tests, Westminster test well

[Tests 4 and 8 were constant-rate tests; drawdowns are for 40-minute pumping durations]

Test number (Date)	Condition	Step	Q Pumping rate (gal/min)	Δs (ft)	ΣΔs (ft)	ΣΔs/Q [ft/(gal/min)]
1 9-14-89	Initial	1	38.4	1.43	1.43	0.037
		2	53.0	1.20	2.63	.050
		3	78.6	1.44	4.07	.052
		4	119	2.51	6.58	.055
2 9-18-89	Brushed and surged	1	40.2	1.19	1.19	.030
		2	59.5	1.06	2.25	.038
		3	82.2	1.49	3.74	.045
		4	122	2.75	6.49	.053
3 9-19-89	Hydro-fracked	1	24.3	.79	.79	.033
		2	60.0	1.31	2.10	.035
		3	79.8	1.37	3.47	.043
		4	149	2.56	6.03	.040
5 10-9-89	Brushed and surged	1	65.0	.95	.95	.015
		2	107	.90	1.85	.017
		3	145	1.49	3.34	.023
		4	250	2.42	5.76	.023
		5	285	1.38	7.14	.025
6 10-31-89	1 raker	1	47.4	.65	.65	.014
		2	109	1.72	2.37	.022
		3	147	1.21	3.58	.024
		4	261	3.99	7.57	.029
7 11-2-89	2 rakers	1	69.0	1.50	1.50	.022
		2	108	1.17	2.67	.025
		3	146	1.30	3.97	.027
		4	262	2.84	6.81	.026

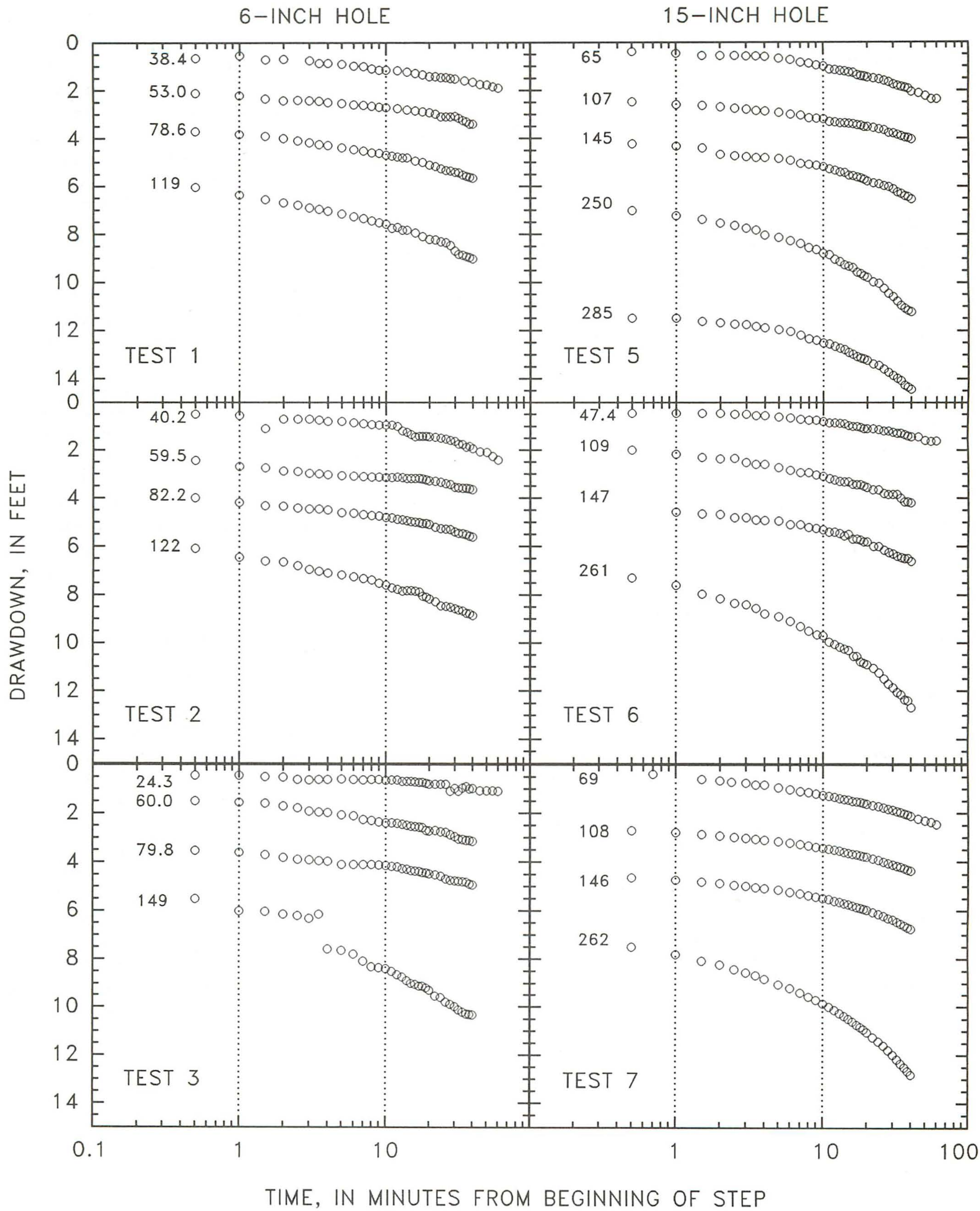


Figure 33.—Time-drawdown relationships from step-drawdown tests. The pumping rate, in gallons per minute, is shown for each step.

wherein s is total drawdown measured in the pumped well; Q is the pumping rate; B and C are constants for laminar head loss and for turbulent losses, respectively. Dividing both sides by Q gives

$$s/Q = B + CQ$$

which is the equation for a straight line having slope C and intercept B. Plots of specific drawdown, s/Q, versus discharge are sometimes referred to as plots of well characteristics.

The ratio of theoretical drawdown (drawdown due to laminar-flow losses in the aquifer) to observed drawdown is the efficiency of the well. Rorabaugh (1953, p. 11) noted that well efficiency drops rapidly when discharge is increased beyond the critical discharge, and is improved with larger well diameter. The intention of the present study was to look for improved well efficiencies by comparing relative magnitudes of the well loss coefficient, C.

Rorabaugh (1953) pointed out that Jacob's test data fell on a curve (meaning the exponent did not equal 2), and described a trial-and-error graphical method to transform the equation to linearity and evaluate the exponent and the constants (However, some workers, e.g. Walton, 1962, feel that letting the exponent equal 2 is adequate for most purposes). Rorabaugh's method only works for data that plot on a concave-upwards curve; otherwise, negative values of B are obtained.

The construction and development treatments that were tested by pumping are listed in table 7. Pumping rates were increased at each step without intervening recovery periods. The step-test data were plotted (fig. 33) in the manner described by Lennox (1966). Incremental drawdowns derived from figure 33 were used to calculate specific drawdowns (the last column shown in table 7). The specific drawdowns are plotted against Q for all of the pumping tests (fig. 34). The two constant-rate tests are represented by a single point each, corresponding to the drawdowns after 40 min of pumping, and are included for comparison.

The well characteristics curves (fig. 34) for the six step-drawdown tests are not linear; indeed, the distribution of points is such that for all of the tests the value of the exponent in Jacob's equation is less than 2 and a negative value of B is obtained. (The coefficients and exponents were calculated using a FORTRAN computer program adapted from Labadie and Helweg, 1975). Mackie (1982) discussed the shapes of plots of well characteristics, noting that a concave-upwards curve was common for wells completed in fractured rocks and that curves that are concave downwards are not common. The latter he attributed to development during pumping or to the effects of radial increases in permeability in some circumstances. Development during pumping can probably be ruled out in the present case. Since B is a function of well radius, the relationship most likely is affected by the voids intersecting the borehole; these extend the effective well radius an indeterminable amount. B is also a function of aquifer storage coefficient, which varies spatially in the vicinity of the well owing to the presence of additional voids and fractures.

Despite the inability to evaluate quantitatively the drawdown components from these data, some aspects are apparent. First, the larger (15-in.) diameter is associated with smaller drawdowns than is the 6-in. diameter. Second, the slopes of the curves of the tests on the larger diameter well are less steep than those of the smaller-diameter well, indicating that turbulent head losses increase less rapidly with increasing pumping rates. The three characteristics curves for the 6-in. diameter well appear to indicate slight improvement with each development procedure; the three curves for the 15-in. well suggest that drilling each raker had a detrimental effect on productivity. These variations in productivity for a particular well diameter may be within the range of uncertainty of the procedures involved in deriving the characteristics curves—thus, we may conclude in the present case that treatments other than increasing well diameter do not appear to have had any significant effect on well productivity.

Immediately following test 3, recovery was measured for 180 min after turning off the pump. Harrill's (1970) modification of the Theis (1935) recovery formula, which applies the principle of superposition of each pumping step, was used to estimate transmissivity (fig. 35). In this figure, time increases to the left. The abscissa is the ratio t^*/t', where t^* is $\Pi t_i^{(\Delta Q_i/Q_n)}$ and t' is the time since pumping ceased. The increments of discharge (ΔQ_i) for each of n steps are superposed for the appropriate elapsed times (t_i), thereby obtaining a parameter that is equivalent to t/t' in the constant-rate analysis. The effects of delayed yield from gravity drainage are evident at early time (t^*/t' greater than about 12) by a decrease in slope. Note that at $t^*/t' = 1$, approximately 1.1 ft of residual drawdown remains, a further indication that the aquifer is limited in extent and the quantity of pumpage was not entirely replenished. Transmissivity estimated from the segment of the graph representing later time (where drawdown behavior follows the linear Theis solution) is 1,320 ft^2/d.

Summary of Pumping-Test Analyses

Analyses of results of pumping and recovery tests produce a range of values for aquifer transmissivity from about 1,320 to about 1,400 ft^2/d (table 8). The heterogeneous nature of the aquifer is evidenced by the drill cores and geophysical logs and by differences in water-level behavior in the two rakers in response to pumping the central well. Linear flow characterized pumping tests conducted at the 15-in. diameter, but not at the 6-in. diameter. Brushing and surging, hydraulic fracturing, and drilling rakers did not significantly improve yield of the test well; increasing the diameter did.

Table 8.—Transmissivity estimates for the Westminster test site

Test	Method	Transmissivity (feet squared per day)
3R	Theis (Harrill) recovery	1,320
4	Neuman type curve	1,400
4	Jacob semi-logarithmic	1,400
4R	Theis recovery	1,320

Note: Test 3R was a recovery from a step-drawdown test conducted on the 6-inch well after brushing, surging, and hydraulic fracturing. Test 4 and 4R were pumping and recovery phases of a 12-hour constant-rate test immediately following test 3R.

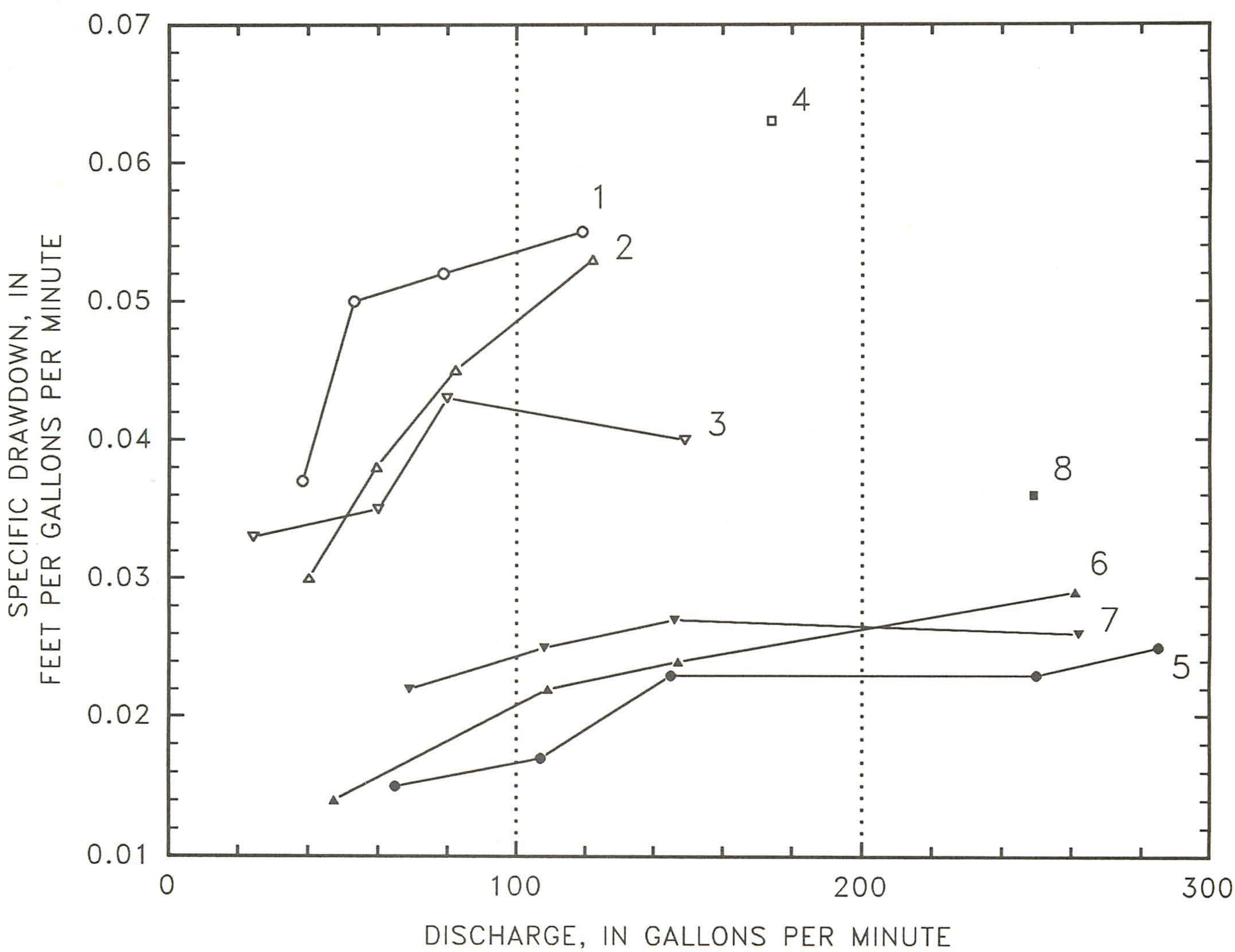


Figure 34.—Well characteristics derived from step-drawdown tests. Numbers refer to treatments: 1, Initial 6-in. well; 2, 6-in. well after brushing and surging; 3, 6-in. well after hydraulic fracturing; 4, 12-hr constant-rate test on 6-in. well; 5, 15-in. well after brushing and surging; 6, 15-in. well with one (uphill) raker; 7, 15-in. well with two (uphill and downhill) rakers; 8, constant-rate test on 15-in. well with two rakers.

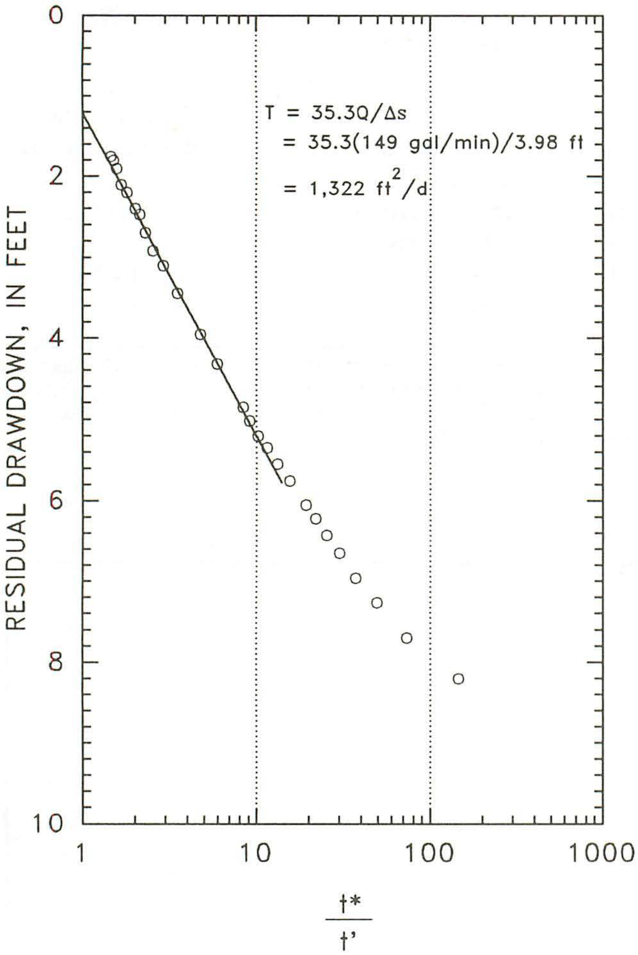


Figure 35.—Recovery following pumping test 3 (step-drawdown test of 6-inch, hydraulically-fractured well). Values of t*/t′ are calculated as described by Harrill (1970), where t* is a function of the times since each step began, and t′ is the time since the pump was turned off.

WATER QUALITY AT WESTMINSTER TEST SITE

A water-quality sample was collected on November 28, 1989, during the final constant-rate pumping test. Properties were measured in the field, and concentrations of basic inorganic ions and nutrients were determined in the laboratory (table 9). The water contains a relatively high amount of chloride (fig. 36; anion milliequivalents per liter consisting of 32 percent chloride), and may be classified as a calcium-bicarbonate-chloride type. Nitrate concentration is also relatively high (19 percent of anion milliequivalents). These concentrations indicate a substantial effect of local land use on ground-water quality—likely sources for chloride and nitrate being road salt and fertilizers, respectively. Ground-water flow, assumed to be predominantly unconfined, is controlled largely by topography and is directed to the northwest; Maryland Rt. 140, to the southeast, crosses the drainage divide and is a potential source of chloride.

With regard to the natural evolution of ground-water chemistry in the vicinity of the test well, it would appear that ground-water flow is short and swift. Chemical equilibria were computed using the thermodynamic-modeling program WATEQF (Plummer, Jones, and Truesdell, 1978). Quartz was the only common mineral with respect to which the water was found to be oversaturated. Most ground-water circulation probably occurs in the upper portion of the bedrock, where calcite has been leached away, and in the cavernous zones, where contact time with the rock is minimal.

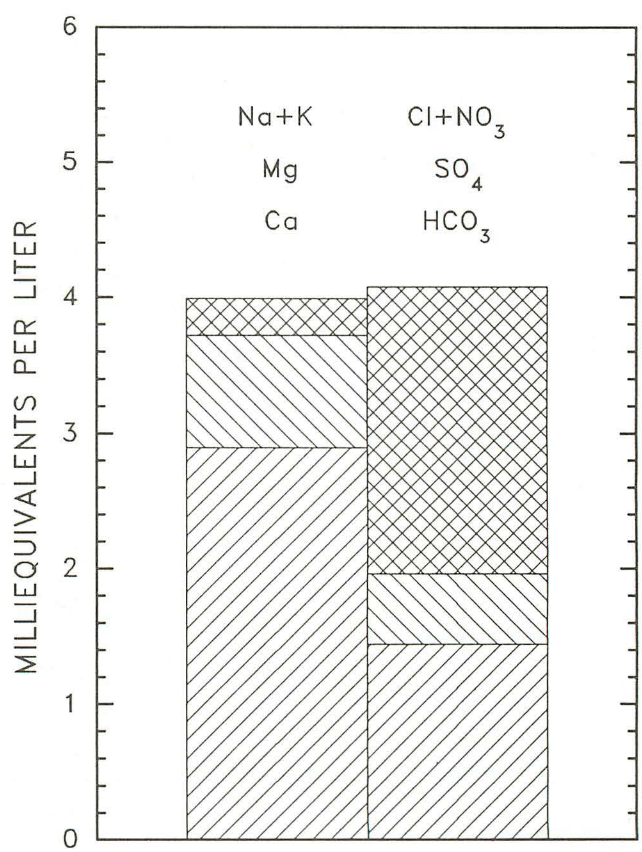


Figure 36.—Composition of water sampled from Westminster test well.

Table 9.—Analysis of water sample from Westminster test well

[Well CL Bd 175, sampled November 28, 1989]

Property or constituent	Value
FIELD MEASUREMENTS:	
Temperature (degrees Celsius)	12
Specific conductance (μS/cm)	435
pH	7.1
Alkalinity (mg/L as $CaCO_3$)	72
LABORATORY:	
Hardness (mg/L as $CaCO_3$)	190
Calcium (dissolved, mg/L)	58
Magnesium (dissolved, mg/L)	10
Sodium (dissolved, mg/L)	5.3
Potassium (dissolved, mg/L)	1.5
Iron (dissolved, μg/L)	5
Manganese (dissolved, μg/L)	3
Sulfate (dissolved, mg/L)	25
Chloride (dissolved, mg/L)	47
Fluoride (dissolved, mg/L)	0.10
Total dissolved solids	
(residue at 180°C, mg/L)	286
(sum of analyses, mg/L)	251
Nitrate + nitrite (dissolved, as N, mg/L)	11
Ammonia + organic nitrogen (dissolved, as N, mg/L)	0.80
Orthophosphate (dissolved, as P, mg/L)	0.02
Organic carbon (dissolved, mg/L)	0.5

SUMMARY AND CONCLUSIONS

The crystalline-rock aquifers underlying most of north-central Maryland are characterized by a strongly skewed well-yield distribution having a preponderance of low values. Municipal and other users commonly require higher well yields than can typically be obtained, and the most productive sites may not be available.

Wells completed in the fractured-rock terrane of Maryland are commonly developed simply by blowing with compressed air through the drill bit upon completion of the well, which may not produce an efficient well. A test well was drilled in marble-bearing phyllite of the Sams Creek Formation in Westminster, Carroll County, to obtain quantitative data on the efficacy of several methods of well construction and development: brushing, surging, hydraulic fracturing, and drilling inclined collectors (rakers). The effect of enlarging the test well from a diameter of approximately 6 in. to approximately 15 in. was also investigated.

The test well began as a vertical, 3-in.-diameter corehole 234.5 ft deep. This was overdrilled at a diameter of 6 in. to a depth of 254 ft. The 6-in. borehole was brushed and surged, and hydraulically fractured. The well was then overdrilled at a diameter of 15 in., and brushed and surged. Two rakers (3-in.-diameter coreholes inclined toward the 15-in. well) were drilled at inclinations of 45° and 37° from the vertical.

Six step-drawdown and two constant-rate pumping tests were conducted at various stages of well construction. Pumping rates for the step-drawdown tests ranged from 24.3 gal/min to 285 gal/min. The analytical methods of Jacob (1947), Rorabaugh (1953), and Labadie and Helweg (1975) could not be applied to the step-drawdown results, apparently because of the heterogeneous nature of the hydrologic system under investigation, in which solutional voids strongly influenced ground-water flow in the vicinity of the well. Nevertheless, data from the step-drawdown tests show no significant beneficial effects on yield due to brushing and surging, hydraulic fracturing, or drilling two rakers. Enlarging the well diameter from 6 to 15 in., however, did result in a significant improvement in well efficiency.

The 6-in. well was pumped at an average rate of about 168 gal/min for 12 hours, and the specific capacity at the end of this period was 8.7 (gal/min)/ft. A second constant-rate pumping test was conducted on the 15-in.-diameter well. The initial pumping rate of 248 gal/min could not be maintained, and after

1,000 minutes dropped off to about 160 gal/min. Specific capacity after 12 hours was 6.9 (gal/min)/ft, and after 24 hours was 5.2 (gal/min)/ft. Recovery was measured after each constant-rate test (and after one of the step-drawdown tests). Water-level behavior during the constant-rate pumping and recovery test conducted on the well at the 15-in. diameter was characteristic of linear flow. This change in behavior from the test at the 6-in. diameter suggests that the larger well with two rakers, which could produce water more efficiently, very quickly passed through a radial flow regime into a regime in which a linear geometry (of voids and/or fracture zones) controlled ground-water flow to the well.

A water sample collected during the constant-rate pumping test of November 28, 1989 represents a calcium-bicarbonate-chloride type. The relatively high concentrations of chloride and nitrate likely reflect local road salting and agricultural fertilizing. The sampled water was undersaturated with respect to all common minerals except quartz, which may reflect rapid ground-water circulation through shallow weathered rock and cavernous zones.

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APPENDIXES

Descriptions of Westminster Test Cores

Geophysical Logs of Westminster Test Well

COREHOLE CL Bd 176

Vertical corehole
Permit number CL-88-0449
Altitude 697 feet

From	To	Description
0	4.5	No recovery.
4.5	9.5	Approximately 2 ft recovered. Clay, reddish-brown with small pebbles and stones approximately 1 in.
9.5	10.3	Clay, brown with yellow streaks; hard.
10.3	14	Clay, red, some rock fragments, saturated at about 11.5 ft.
14	15	Phyllite, green, weathered, showing relict structure; a hard rock fragment about half way prevented complete drilling with this flight.
15	24.5	Harder drilling at about 20 ft; Mud, brown and wet, becoming greenish-brown and more viscous.
24.5	24.8	Rock, weathered, green with some maroon, crumbly, some pieces hard, some soft; 50 blows to hammer split spoon 0.3 ft.
24.8	29.5	Green phyllite with vertical fractures and voids and some quartz(?) mineralization.
29.5	34.5	Similar to above, but fractures becoming somewhat more inclined; fracture near top showing red clay on surface; some black mineralization of fracture surfaces.
34.5	36.3	Similar to above, but with streaks of marble.
36.3	37	Dark gray phyllite.
37	40.2	Void; lost water.
40.2	42	Similar to material above void, but with marble streaks; some clay on surfaces near void.
42	43.3	Marble with streaks of chlorite(?).
43.3	44.5	Mixed lighter-green (epidote?) and marble.
44.5	45.5	Light gray marble with thin streaks of chlorite(?).
45.5	53.5	Void; did not lose water.
53.5	54.5	Clay on surface below void; light gray marble with thin streaks of chlorite(?).
54.5	58.7	Less marble with depth.
58.7	59.5	Void.
59.5	64.5	Similar to material above void.
64.5	74.5	Green phyllite with streaks of calcite or quartz to about 72.4 ft, streaks below are mostly quartz.
74.5	79.2	Dark gray phyllite, a few thin white streaks.
79.2	83.3	Mostly massive marble with a nearly vertical quartz vein.
83.3	84.5	More phyllite.
84.5	97.6	Marble mixed with phyllite.
97.6	99.9	Mostly green phyllite, some purple.
99.9	104.5	Mostly marble with some quartz.
104.5	114.5	Phyllite mixed with marble; some quartz in marble.
114.5	124.5	Mostly green phyllite with some thin (<0.05 in.) marble.

COREHOLE CL Bd 176, Continued

124.5	144.5	Mostly green phyllite, with thin, mostly vertical streaks of marble; no quartz.
144.5	154.5	Similar to above; breaks in core are mostly steep to horizontal with no evidence of weathering.
154.5	164.5	Similar to above, but some quartz present; a little epidote near bottom.
164.5	176	Mostly green phyllite; thicker seams of quartz with some calcite; some small mica grains scattered throughout.
176	182.5	Similar to above, but coarser-grained with some vertical breaks along foliation.
182.5	194.5	Similar to above, but more thin seams of calcite; pink dolomite at 189 ft; hint of weathering on fracture surface at 185.8 ft.
194.5	224.5	Similar to above, with more epidote at 197 - 198.5 ft; some quartz; vertical fracture at about 212.7 - 219 ft with purplish-red (10R2.5/2) stain.
224.5	234.5	Metabasalt with thin seams of calcite and quartz; bottom of hole.

COREHOLE CL Bd 177
First (uphill) raker
Permit number CL-88-0450
Altitude 711 feet

From	To	Description
0	35	Soil and overburden.
35	51	Overburden, wet and more clayey.
51	62	Rock.
62	78.5	Soft, not recovered.
78.5	88.5	Became harder toward bottom; recovered about 0.4 ft at bottom.
88.5	98.5	Soft; recovered about 1 ft. Weathered and fractured green phyllite, iron and manganese staining on fractures.
98.5	108.5	Similar to above; steep apparent dip of foliation; about 2 ft recovered.
108.5	113.5	About 1.5 ft recovered; soft green weathered phyllite under about 0.4 ft of mud. Apparent dip of foliation approximately 45 degrees; iron and manganese staining on fractures; thin (<0.05 in.) quartz seams.
113.5	123.5	Weathered green phyllite; manganese and iron staining of fractures; quite porous (dissolution of calcite); some thin quartz seams; core mostly broken; softer near bottom.
123.5	128.5	Mostly broken, weathered green phyllite, with steep apparent dip of foliation; iron and manganese staining of fractures; some epidote near bottom.
128.5	133.5	Numerous small voids, hole taking water; somewhat less weathered green phyllite, thin zones of epidote and zones of marble and quartz.
133.5	138.5	Broken up weathered green phyllite, chunk of quartz on top; iron and manganese staining of fractures.
138.5	143.5	Broken, weathered green phyllite, very soft near top; apparent dip of foliation about 30 - 45 degrees.
143.5	148.5	Broken, weathered phyllite, with some epidote and a quartz seam about 0.1 ft thick.
148.5	153.5	Broken and weathered green phyllite; iron and manganese staining of fractures; some quartz seams; an overturned, tight fold.
153.5	158.5	Broken up green phyllite and schist with some quartz and iron and manganese staining of fractures.
158.5	168.5	Similar to above, but quartz veins absent; coarser, less green and more silvery at about 163 ft.
168.5	171	Very weathered and broken up rock.
171	174	Void.
174	178.5	Fresh green phyllite mixed equally with calcite.
178.5	188.5	Fresh green phyllite mixed with calcite and some quartz; some staining on three fracture surfaces.
188.5	190.9	Similar to above, with very steep apparent dip of foliation.
190.9	198.5	Mostly dark green phyllite/schist with some quartz and calcite; apparent dips mostly 35 - 45 degrees; some cross-cutting veins and some folding.

COREHOLE CL Bd 177, Continued

198.5	208.5	Similar to lower part of above section; some quartz, and lesser amounts of calcite; maroon stain on break at 201.5 ft; about 0.1 ft of offset of some faulted veins at about 203 ft.
208.5	218.5	Fresh green phyllite/schist with numerous thin calcite and quartz veins dipping (apparent) at about 45 degrees.
218.5	228.5	Green phyllite with numerous thin quartz seams, some calcite at bottom; slight maroon staining of fracture at 219.5 and 220.5 ft; displacement along fracture near top.

COREHOLE CL Bd 178
Second (downhill) raker
Permit number CL-88-0451
Altitude 690 feet

From	To	Description
0	12	No recovery.
12	18	Green phyllite mixed with thin seams of quartz; porous at top and bottom.
18	18.5	Soft, perhaps a void.
18.5	26	Weathered, porous green phyllite with much staining.
26	31	Broken at the top 0.3 ft; green phyllite/schist with some thin quartz veins, some epidote; soft at bottom.
31	41	Thin, interlaminated green phyllite, epidote, and quartz; offset fracture near top showing maroon staining; broken up at top and bottom.
41	51	Similar to above; somewhat porous at top 3 ft.
51	61	Similar to above, but no broken, weathered material; calcite absent; foliation has apparent dip of about 45 degrees.
61	71	Similar to above, but some quartz veins a little thicker.
71	81	Similar to above; one fracture surface showing slight maroon stain at 74 ft; some calcite.
81	91	Similar to above, but with black mineral grains disseminated near top and bottom, and more calcite.
91	101	Somewhat more schistose than material above; zone of epidote at about 93.5 ft; very little calcite, some black mineral scattered near top and bottom.
101	111	Thin interlaminations of green phyllite, quartz, and calcite; some epidote; maroon staining on fracture surface at about 102 ft; slightly open, partly-healed fracture at 105.2 ft.
111	121.5	Green epidote and phyllite with some quartz to about 116 ft, becoming mostly quartz and greenish-blue phyllite; maroon staining on a few fractures.
121.5	136	More epidote, fewer quartz zones; some very slightly offset faulted veins of quartz; texture mostly granular.
136	141	Texture more phyllitic than above, with many quartz seams and no calcite.
141	151	Similar to above, but with a small amount of calcite; maroon-stained fracture at about 149 ft.
151	161.7	Similar to above; some offset faulting with kink folds at about 162 - 163 ft; more schistose near bottom.
161.7	171	Green phyllite with epidote and quartz veins; some maroon staining on two fractures.
171	182	Somewhat schistose, greenish-blue rock with many quartz veins; very small amount of calcite; some staining of fracture surfaces.
182	182.3	Quartz.
182.3	191	Blue schist with much quartz mixed in.

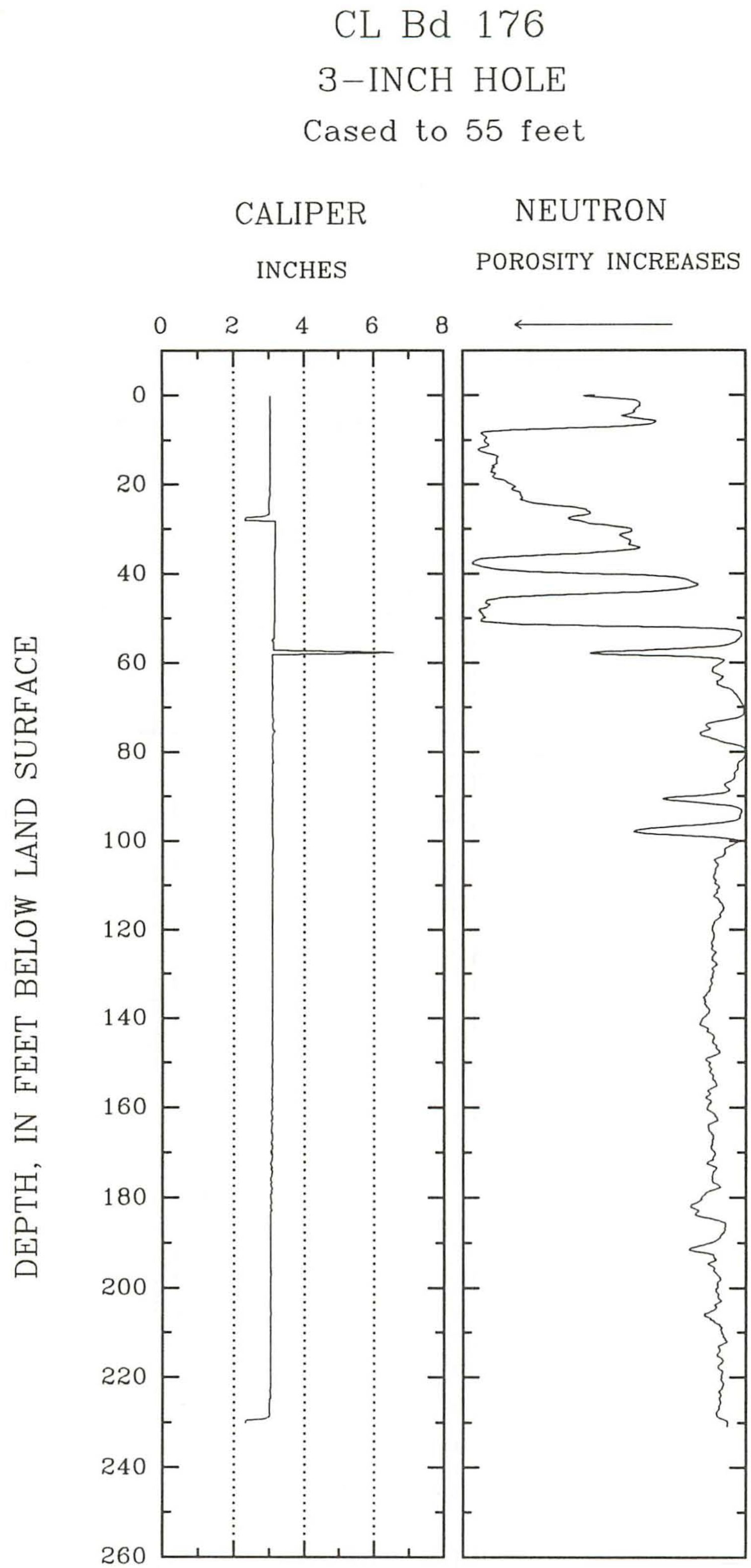

Figure 15.—Geophysical logs of Westminster test well.

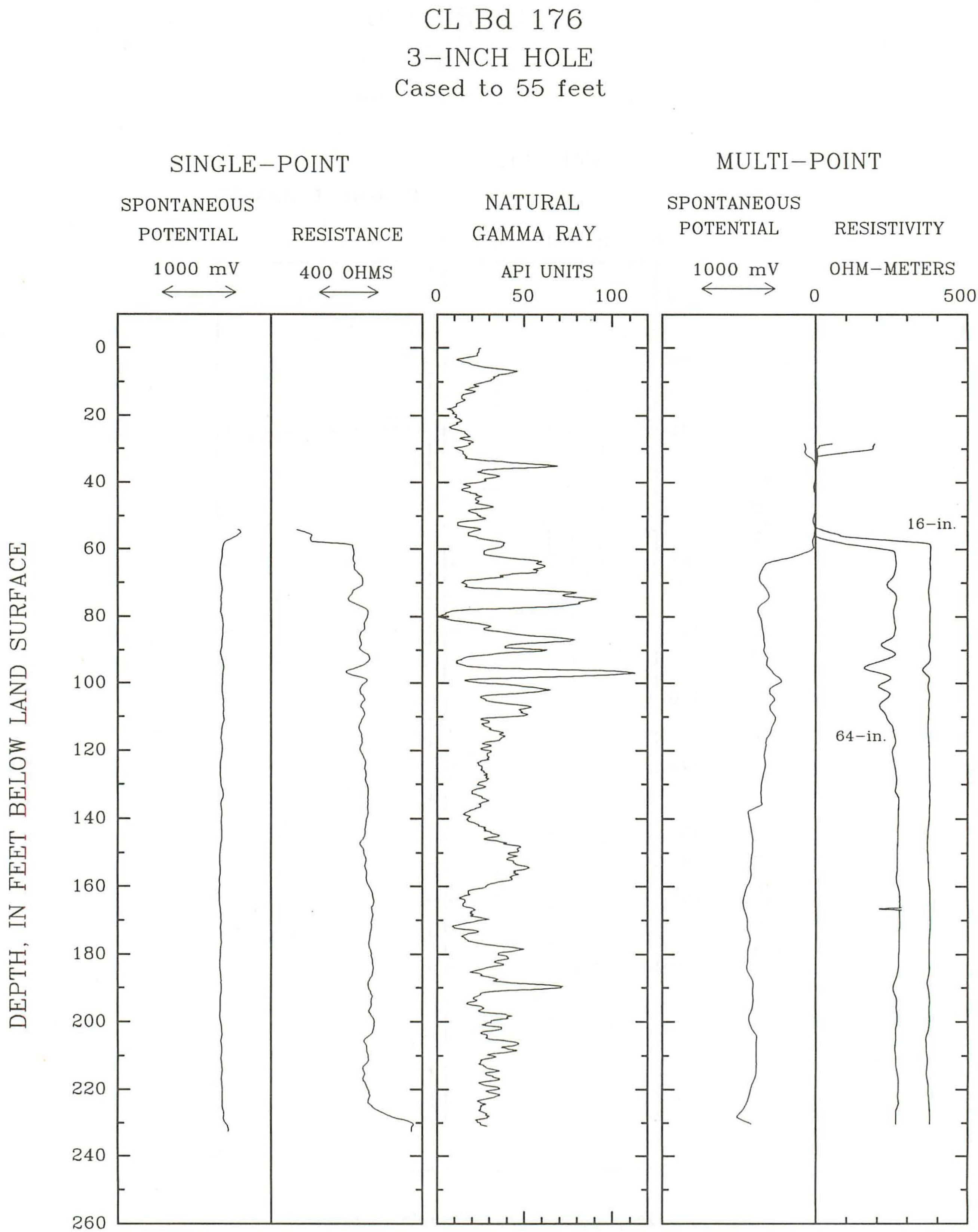

Figure 15.—Continued.

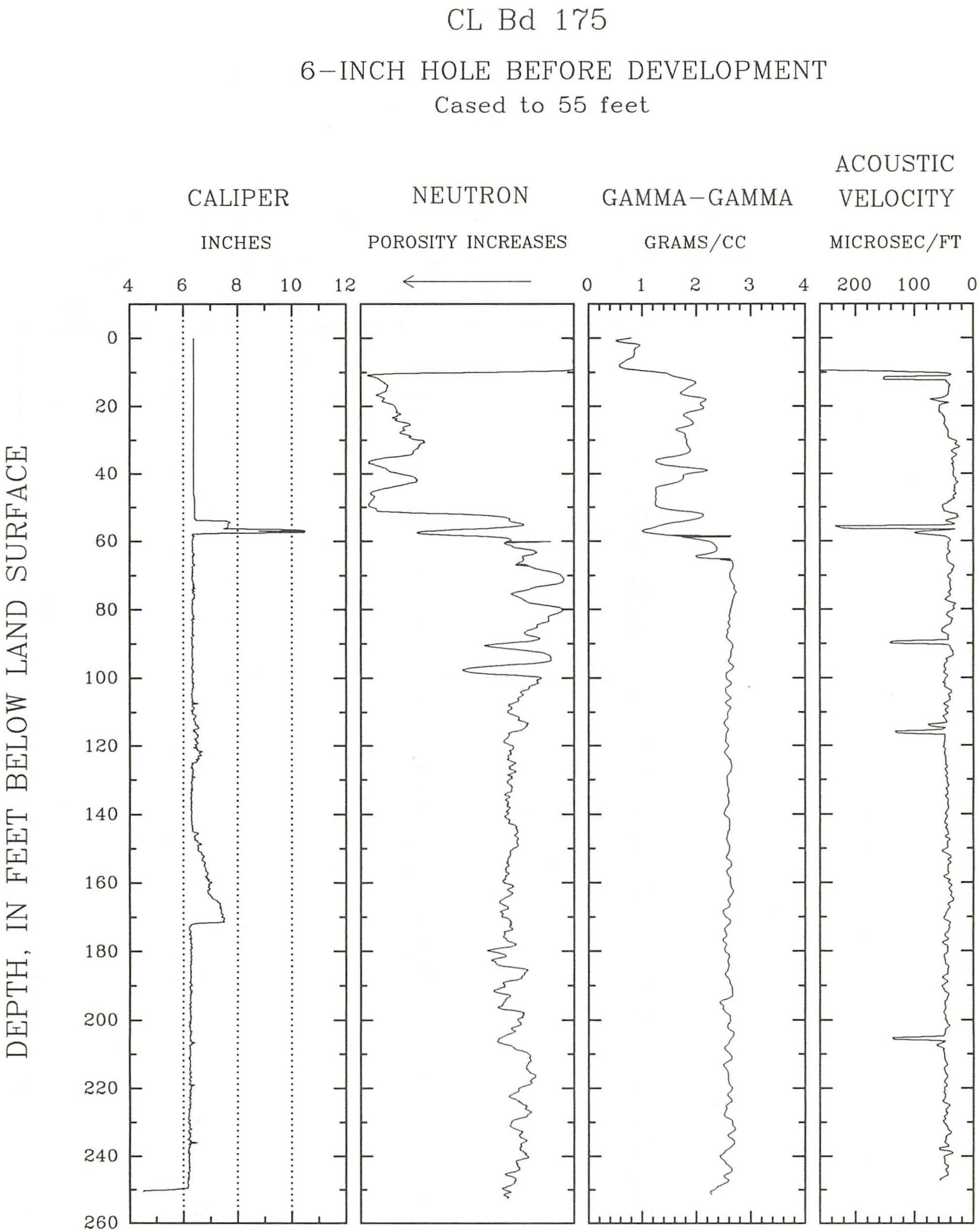

Figure 15.—Continued.

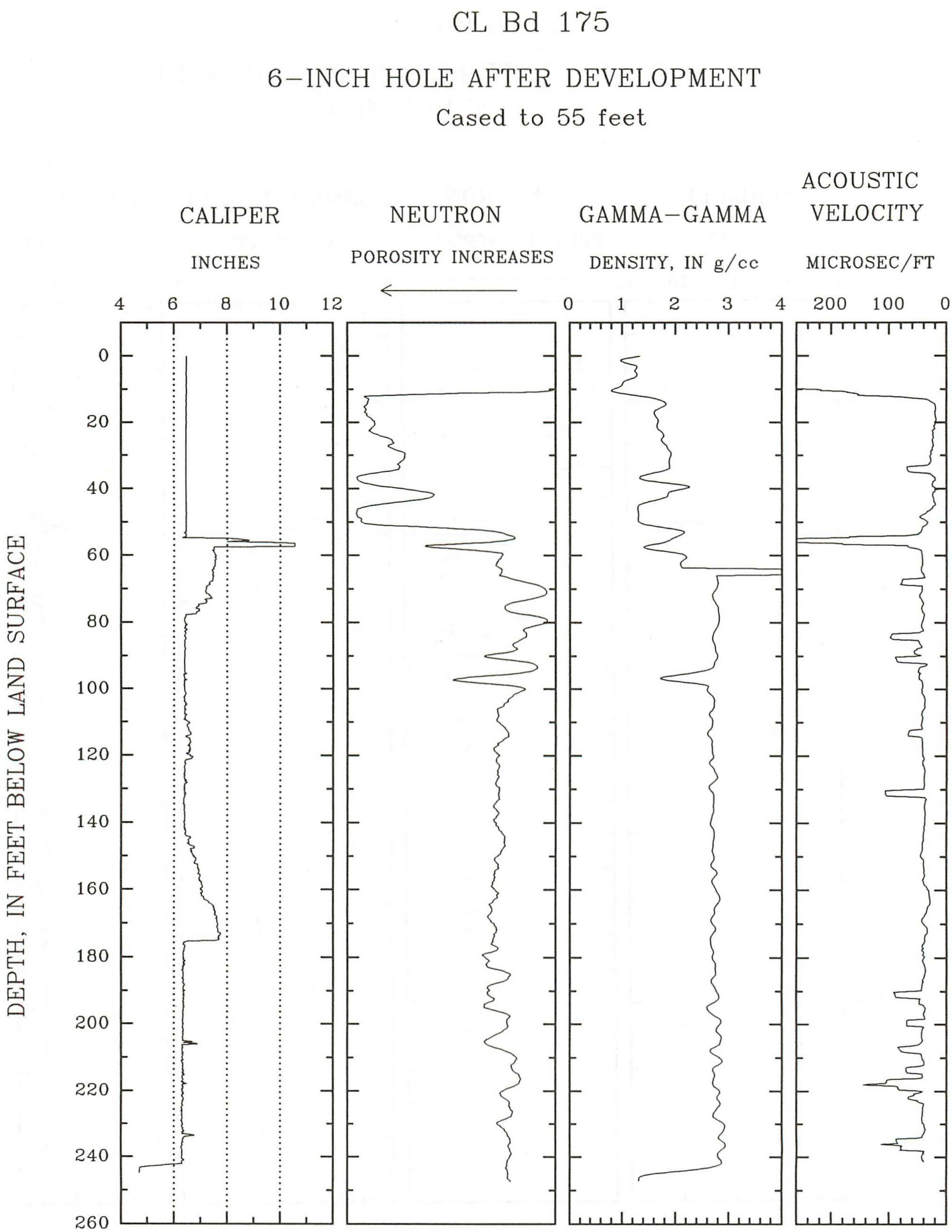

Figure 15.—Continued.

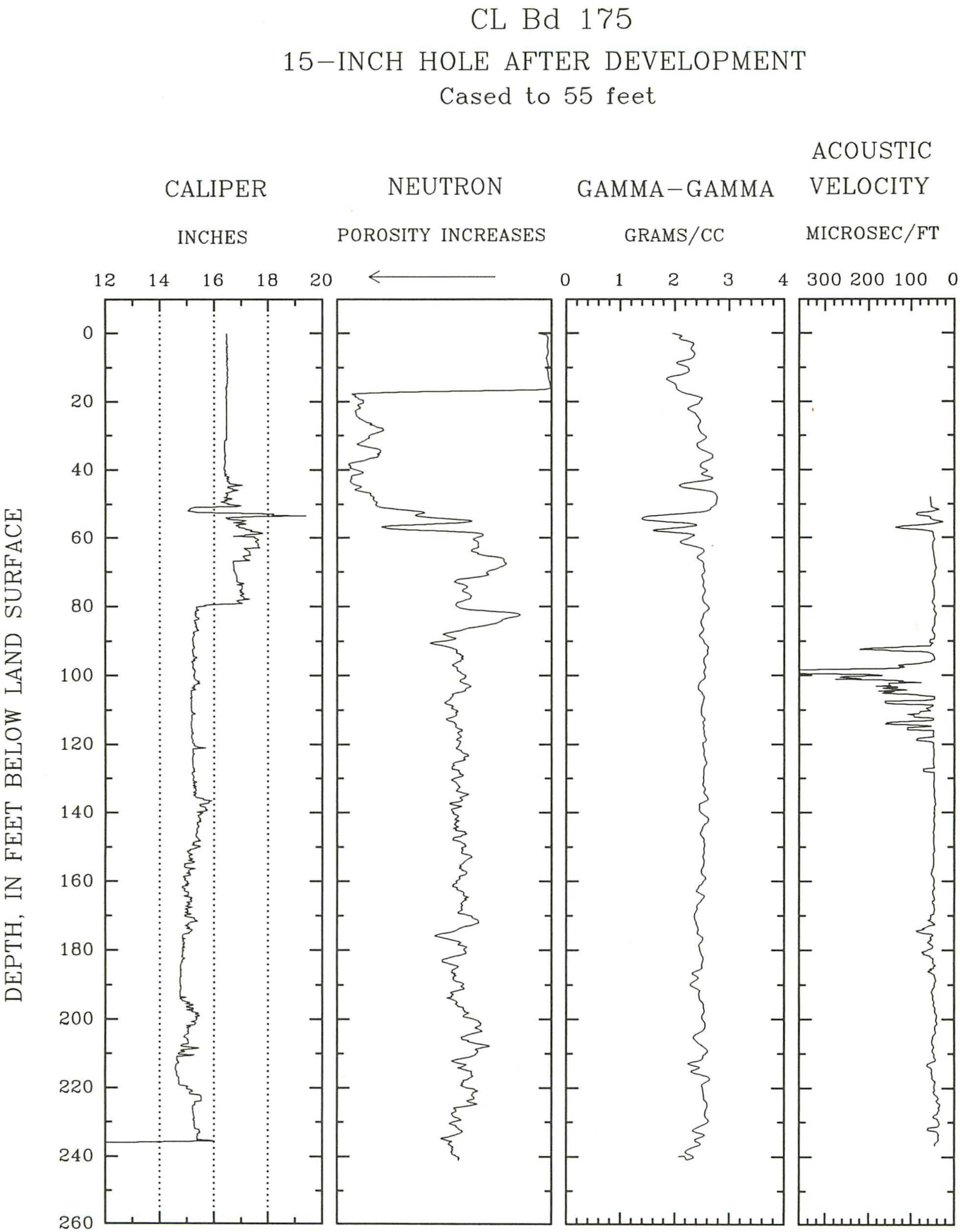

Figure 15.—Continued.

Plate 1.—Acoustic televiewer logs of the 3-inch corehole and the 6-inch and 15-inch boreholes.

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