NATIONAL TRANSPORTATION SAFETY BOARD
Investigative Hearing
Washington Metropolitan Area Transit Authority Metrorail train 302 that encountered heavy smoke in the tunnel between the L'Enfant Plaza Station and the Potomac River Bridge on January 12, 2015

GROUP	H
EXHIBIT	
29	

Agency / Organization

Washington Metropolitan Area Transit Authority

Title

United States Geological Survey Water Resources Investigative Study

Docket ID: **DCA 15 FR 004**

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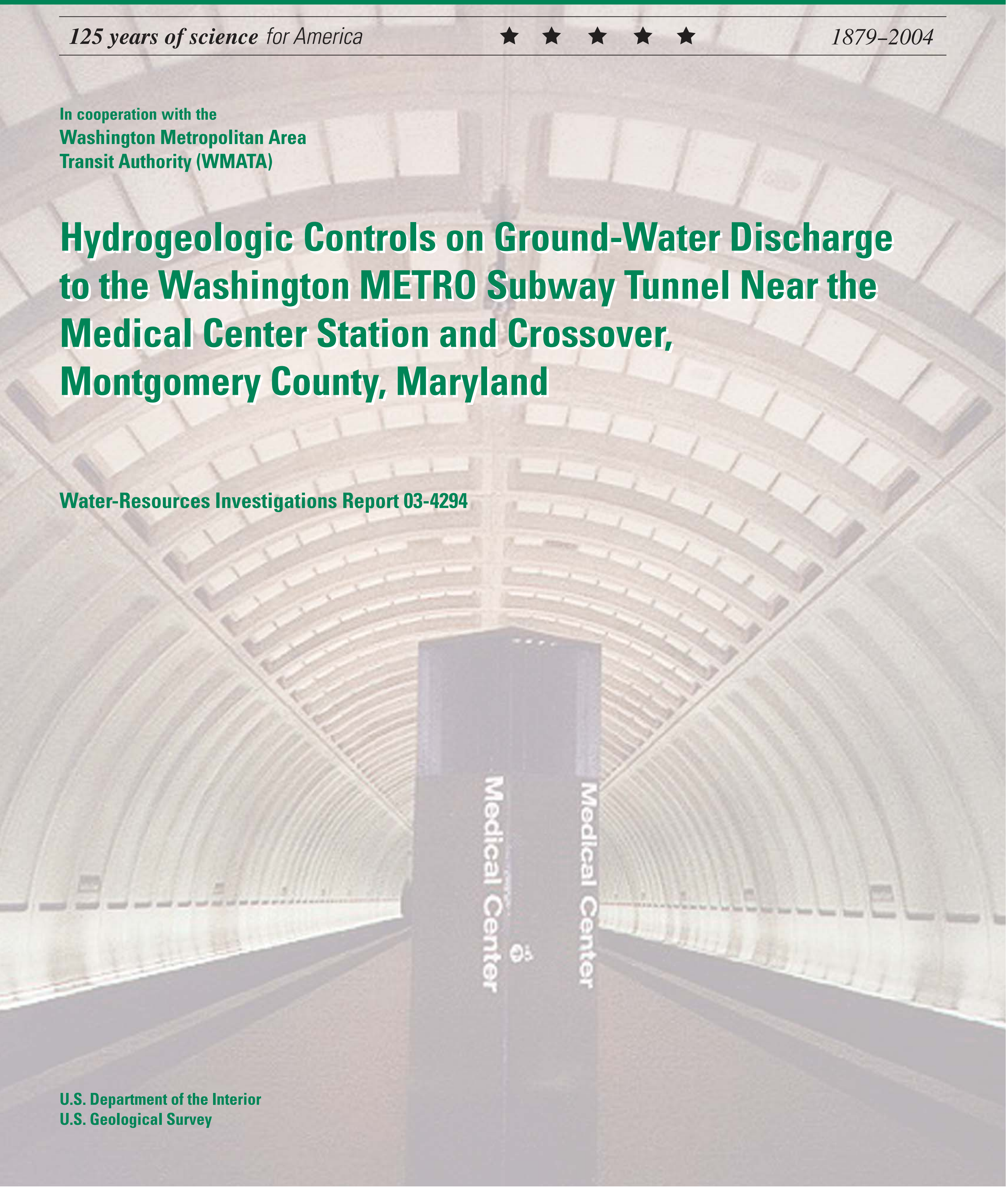
In cooperation with the
Washington Metropolitan Area
Transit Authority (WMATA)

Hydrogeologic Controls on Ground-Water Discharge to the Washington METRO Subway Tunnel Near the Medical Center Station and Crossover, Montgomery County, Maryland

Water-Resources Investigations Report 03-4294



U.S. Department of the Interior
U.S. Geological Survey

Cover. Washington METRO subway tunnel near the Medical Center Station and Crossover, Montgomery County, Maryland

[Cover photograph courtesy of Washington Metropolitan Area Transit Authority.]

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Hydrogeologic Controls on Ground-Water Discharge to the Washington METRO Subway Tunnel Near the Medical Center Station and Crossover, Montgomery County, Maryland

by Earl A. Greene, Allen M. Shapiro, and Andrew E. LaMotte

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125 years of science *for America* ★ ★ ★ ★ ★ *1879–2004*

Reston, Virginia
2004

U.S. Department of the Interior
GALE A. NORTON, Secretary

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CONTENTS

Figures

Figures—Continued

Tables

Conversion Factors and Vertical Datum

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
[1] foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

[1] The standard unit for transmissivity is cubic foot per day per square foot [($ft^3/d)/ft^2$] times the aquifer thickness. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Vertical Datum: In this report, “sea level ” refers to the National Geodetic Vertical Datum of 1988—a geodetic datum derived from a 1988 update of the reference geoid and first-order level nets of the United States and Canada.

Altitude refers to the height above mean sea level and **Elevation** refers to the height above a defined reference datum. The reference datum used throughout this report is mean sea level, so in this instance, the terms are interchangeable.

Hydrogeologic Controls on Ground-Water Discharge to the Washington METRO Subway Tunnel Near the Medical Center Station and Crossover, Montgomery County, Maryland

By Earl A. Greene, Allen M. Shapiro, and Andrew E. LaMotte

Abstract

Excessive water intrusion has been observed inside several of the Washington Metropolitan Area Transit Authority subway tunnels, with the worst leakage occurring along the Red Line tunnels and stations north of Dupont Circle in Washington, D.C. These tunnels were constructed in bedrock that contains permeable (water-bearing) joints and fractures. Excessive water leakage through the walls and water inside the underground facilities has damaged mechanical and electrical components in the tunnel, and has escalated the deterioration rate of the rail system. The U.S. Geological Survey and the Washington Metropolitan Area Transit Authority have worked cooperatively on a study from 2000–03 to describe and quantify the factors controlling ground-water flow into the Red Line subway tunnel near the Medical Center Station and Crossover in Montgomery County, Maryland.

The Red Line near the Medical Center Station and Crossover passes through or beneath the gneissic Sykesville Formation and the biotite-hornblende tonalite member of the Georgetown Intrusive Suite, both of which contain numerous fractures. The mapped foliation and joints of the Sykesville Formation in the vicinity of the Medical Center Station and Crossover are generally orientated north-south. Fractures in the Sykesville Formation in outcrops appear to be poorly connected. In the biotite-hornblende tonalite member of the Georgetown Intrusive Suite, the general orientation of the mapped foliation and joints is east-west. In contrast to the fractures in the Sykesville Formation, the fractures in the Georgetown Intrusive Suite in outcrops appear to be more numerous and have a greater degree of connectivity. Fractures intersecting four bedrock wells near the Medical Center Station and Crossover that were drilled into the biotite-hornblende tonalite member of the Georgetown Intrusive Suite show an east-west orientation matching the foliation and joints shown on geologic maps. The excessive water intrusion at the Medical Center Station and Crossover could be the result of its location within the Georgetown Intrusive Suite. The abrupt changes in the mapped directions of ground-water flow based on the hydraulic heads at the contact between the Sykesville Formation and biotite-hornblende tonalite member of the Georgetown Intrusive Suite could also be the result of the change in fracturing between these two lithologies.

Saprolite, a residual of soft, red/brown to gray clay from decomposed crystalline rock, overlies the bedrock and varies from about 20 to 55 feet thick, depending on location. On the basis of a slug test conducted in the lower part of the saprolite near the Medical Center Station and Crossover, transmissivity and storativity of the saprolite were estimated to be 10 feet squared per day and 10^{-6}, respectively.

The transmissivity of fractures intersecting bedrock boreholes drilled in the biotite-hornblende tonalite member of the Georgetown Intrusive Suite varies over five orders of magnitude, from a maximum of approximately 10 feet squared per day to the detection limit of the *in situ* testing apparatus, which is approximately 10^{-4} feet squared per day. In general, the transmissivity of fractures intersecting the boreholes increases with depth. The low transmissivity of bedrock fractures in close proximity to the saprolite is likely to be caused by the fractures being filled with byproducts of rock weathering, resulting in reduced permeability.

The bulk transmissivity of the bedrock aquifer is approximately 3.7 feet squared per day, as determined from an aquifer test conducted by pumping a 240-foot-deep borehole and monitoring the drawdown over 3 days in the pumped borehole and several observation boreholes.

In general, the hydraulic head decreases with depth in bedrock boreholes, indicating the potential for downward ground-water flow. Based on hydraulic head values measured in the boreholes and this potential for downward ground-water flow, the saprolite may be recharging the bedrock aquifer.

Introduction

Between 1966 and 2001, the Washington Metropolitan Area Transit Authority (WMATA) designed and built a 103-mile rail system that services Washington, D.C. and parts of Maryland and Virginia; approximately one-half of the rail system is underground. Excessive water intrusion has been observed inside several of the tunnels with the worst leakage occurring along the Red Line (figs. 1a–1b). The Red Line tunnels, stations, and crossovers north of Dupont Circle were constructed in bedrock that contains permeable (water-bearing) joints and fractures.

The Red Line tunnels were constructed prior to the early 1980s, when no proven water-sealing technologies were available to effectively mitigate water intrusion by sealing the tunnel walls. In addition, tunnel-boring machines are incapable of constructing the shape of a crossover and station. A crossover is a cavernous structure, approximately 40 ft (feet) high and 100 ft wide, utilized for the “crossing over” of trains from track to track. Drilling and blasting techniques were utilized in the construction of the station areas and crossovers in the fractured bedrock along the Red Line, and the walls were supported with steel ribs and pneumatically applied concrete (shotcrete).

Tunnels are typically designed to permit a limited amount of leakage through the lining. This water is usually collected in a drain system and then pumped back to the surface for disposal. WMATA design specifications to prevent water intrusion into the Red Line were based on a Hydrostatic Pressure Relief System (HPR). This system would convey water from outside of the tunnel lining to the track drains. The tunnel lining was allowed to conduct a small amount of leakage—about 0.1 gal/min (gallons per minute) per 100 ft of tunnel. Mineral deposits clogged many of the relief ports soon after construction, and about 1 out of every 10 ports are in good working order (Capital Transit Consultants, 2001).

Shortly after construction, noticeable amounts of water began to leak from cracks, voids, and construction joints in the tunnel linings. Excessive water leakage through the walls and the presence of water inside the underground facilities has damaged mechanical and electrical components in the tunnel, and has escalated the deterioration rate of the rail system. This leakage will eventually reduce the life span of the structure and rail system. Current water mitigation practices include the application of sealants to cracks that are leaking or diverting flow from the ceiling to the drain system with small “aluminum tents” (fig. 2).

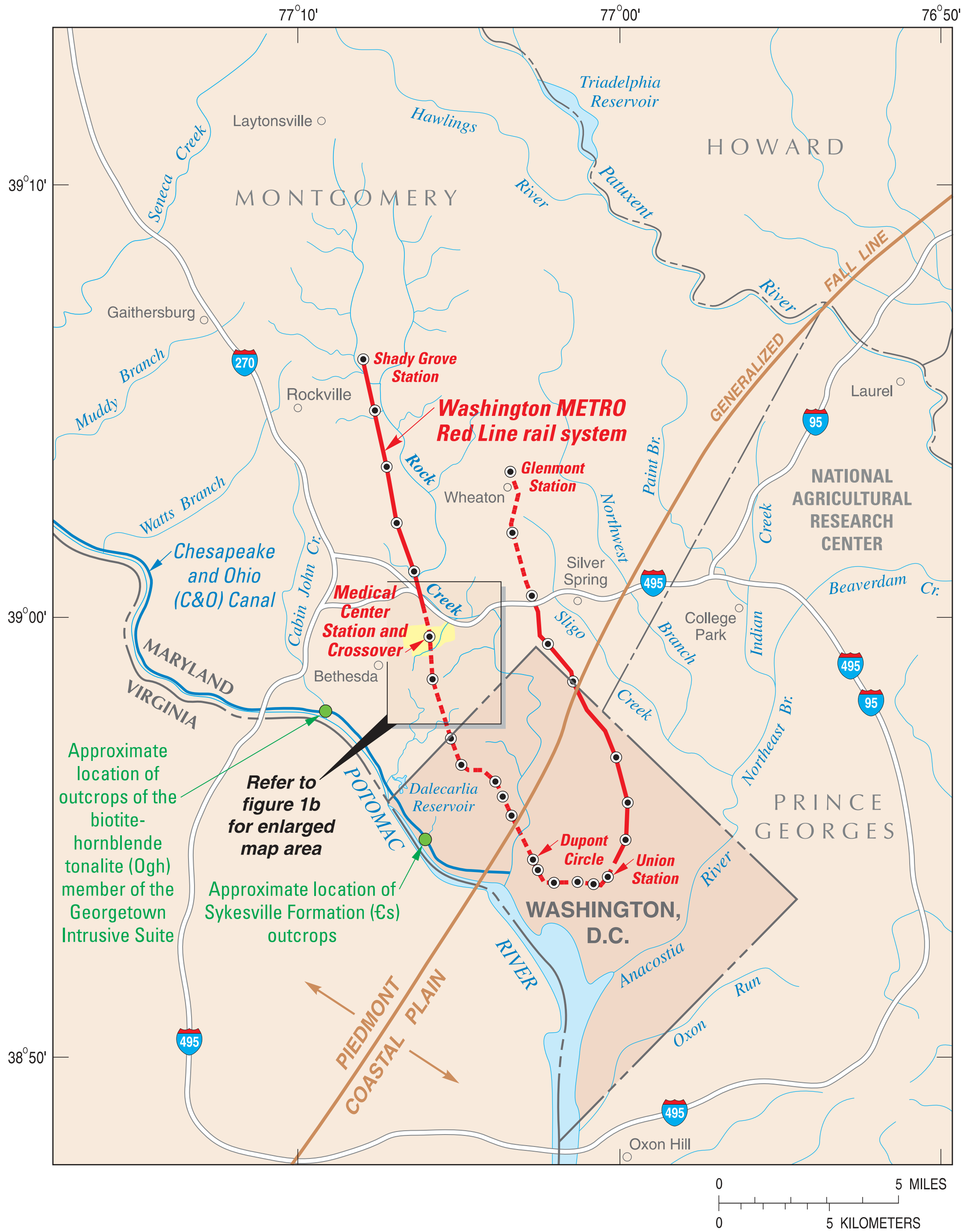
Water intrusion inside the crossovers along the Red Line is more severe than in other parts of the subway system. These crossovers are supported by steel ribs with a thin layer of shotcrete and do not contain a waterproofing membrane. In general, the structural performance of the crossovers has been satisfactory up to now, but due to excessive water leaks, the life expectancy of the electrical and mechanical infrastructure and structural members in the proximity of the crossovers may be less than in other locations (Capital Transit Consultants, 2001). In order for the engineers and managers of WMATA to develop a strategy to prevent or reduce water intrusion inside the underground facilities, an understanding of the hydrogeologic controls on water intrusion is needed. The U.S. Geological Survey (USGS) and WMATA worked cooperatively on a hydrogeologic investigation to characterize ground-water flow into the tunnel system from 2000–03. The results of this study will provide a methodology for investigating similar water intrusion problems at other sites constructed in fractured bedrock along the subway system, and provide information useful in the design of methods to divert or reduce the volume of water entering the subway tunnels.

Purpose and Scope

This report describes an investigation to determine the hydrogeologic factors controlling ground-water inflow into the Medical Center Station and Crossover on the Red Line. This part of the Red Line was chosen for investigation by WMATA and the USGS because of the severity of the water intrusion at this location. The Medical Center Station and Crossover is located in Bethesda, Maryland, adjacent to the National Institutes of Health (NIH) and the National Naval Medical Center (NNMC) (fig. 1b). The Medical Center Station and Crossover is approximately 48 ft high and was constructed approximately 140 ft below land surface (190 ft above mean sea level).

Several methods of investigation were used to characterize the hydrogeology, and investigate ground-water discharge from bedrock to the Medical Center Station and Crossover. Previously published geologic maps, surface geophysics, and data from existing wells in the area were used to evaluate the extent of the saprolite and bedrock. Water levels in the bedrock were mapped and correlated to structural features. In addition, temporal water-level fluctuations were analyzed at observation wells completed in the saprolite and bedrock.

Four bedrock and one saprolite test wells were drilled as part of the study and were used to investigate and character-



EXPLANATION

LOCATION OF THE WASHINGTON METRO RED LINE RAIL SYSTEM AND STATIONS (Dashed line indicates underground portion of the Red Line.)

Figure 1a. Location of the Washington METRO Red Line and Medical Center Station and Crossover, Montgomery County, Maryland.

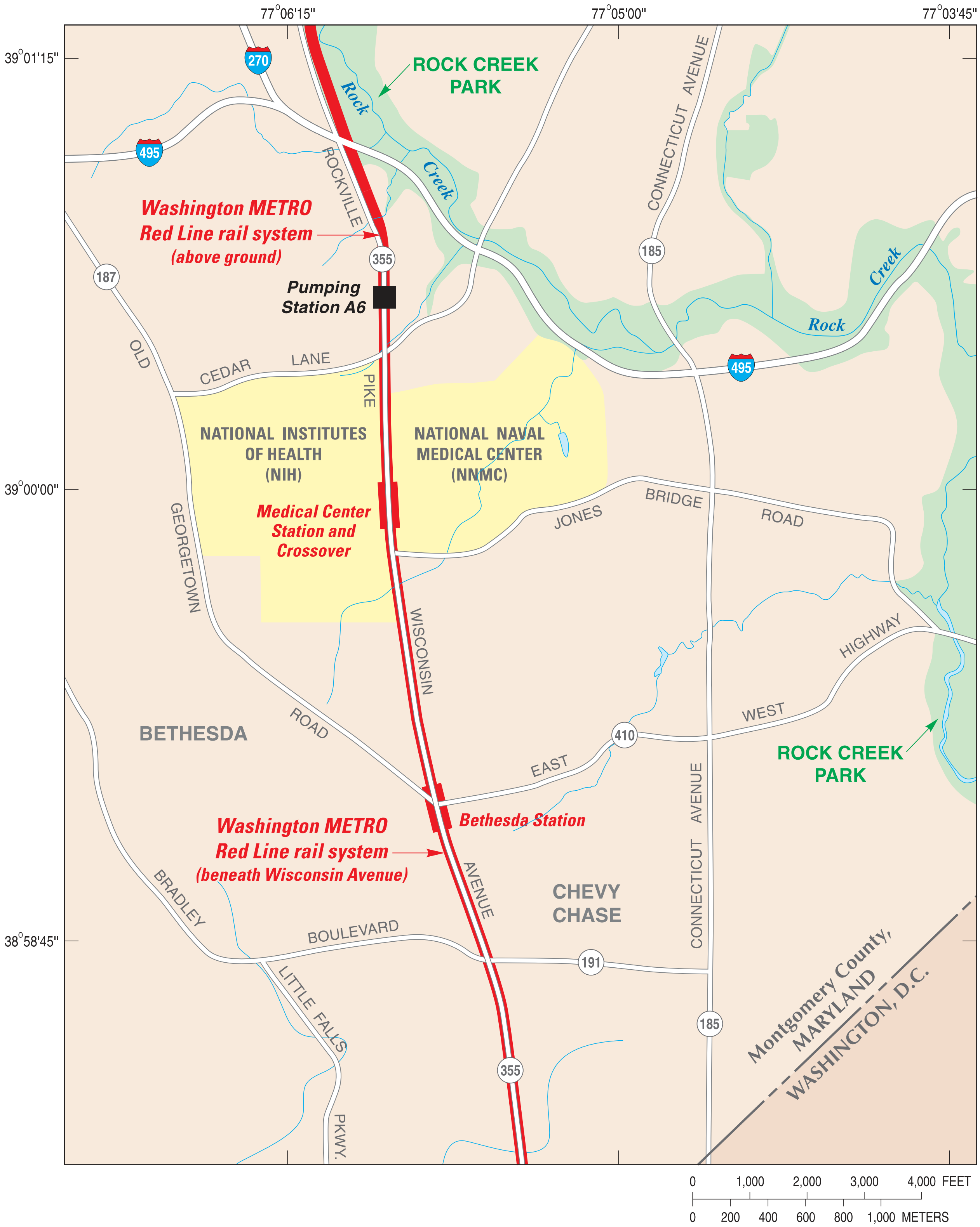


Figure 1b. Location of the Medical Center Station and Crossover, the National Institutes of Health, and the National Naval Medical Center, Montgomery County, Maryland.

(A)

(B)

Figure 2. Photographs showing: **(A)** the interior of the Medical Center Station and Crossover, and **(B)** close-up along a tunnel wall of the "aluminum tents" installed to divert water leaking from the ceiling.

ize the physical properties of the bedrock. Analysis of borehole geophysical logs provided information on the location and orientation of the fractures.

Aquifer tests consisting of a slug test in the saprolite and single and multiple well tests in the bedrock were used to determine the transmissivity and storativity of the formations. An air-pressurized slug test conducted in the saprolite gave information on the hydraulic properties of this formation. Single well tests (packer tests) conducted in the bedrock provided hydraulic information on fractures within an isolated portion of the borehole. A multiple-hole hydraulic test was conducted over a longer period of time to infer the bulk transmissivity of the bedrock.

Inflow of ground water into the tunnel near the Medical Center Station and Crossover was measured by recording discharge at the A6 pumping station. Discharge was then correlated with observed hydraulic head data measured in the bedrock.

Previous Investigations

WMATA personnel and various engineering and consulting firms have conducted several investigations to characterize water intrusion inside the tunnels since they were constructed. The first major investigation was conducted by Mueser Rutledge Consulting Engineers (1988), who looked at the reasons for the leakage. They concluded that the intensity of leakage in the tunnel was a result of various factors including the calcification of the HPR system, the permeability of the surrounding ground, ground-water pressure conditions, acid water from soils, and cracks in the cast-in-place concrete.

Additional investigations to characterize water intrusion into the Red Line, specifically at the Medical Center Station and Crossover, have been conducted by Capital Transit Consultants, Inc. (2001) and DMJM/Deleuw, Cather & EBA Engineering, Inc. (2001). These firms concluded that the blasting utilized to construct the crossover and station areas may have intensified fracturing of the bedrock near the tunnel. Other factors they identified that could be affecting water intrusion may be shrinkage cracks along the tunnel and construction joints in the concrete.

Acknowledgments

The authors would like to thank the employees of Mueser Rutledge Consulting Engineers, Bechtel Associates Inc., and others who researched their files for information regarding the original construction notes and subsequent water-intrusion investigations of the Red Line. In addition, the authors would like to thank Harry Lupia, John Rudolf, and James Darmody of WMATA for their insights on water intrusion into the tunnel, historical and engineering knowledge of tunnel construction practices, and local geologic information. Colleague reviewers Forest Lyford and Richard Yager of the USGS are thanked for their thoughtful comments and suggestions. Special thanks go to Valerie Gaine, Jean Hyatt, Donna Knight, and Timothy Auer of the USGS for editorial reviews, report preparation, and report graphics. Lastly, the authors would like to acknowledge the assistance of U.S. Navy personnel, including Patrick Whittington and William Freeman, for their logistical support and assistance in obtaining needed permissions to work at the National Naval Medical Center.

Geologic Setting

The study area is located in the Maryland part of the Piedmont and Blue Ridge Region (Heath, 1984). The Piedmont part of this region is characterized by low, rounded hills, with long, rolling northeast-southwest trending ridges whose summits range from about 300 ft along its eastern boundary with the Coastal Plain to about 1,500 to 1,800 ft along its western boundary with the Blue Ridge. The Piedmont is underlain by bedrock of Precambrian and Paleozoic age consisting of igneous and metamorphosed igneous and sedimentary rocks (Heath, 1984). The rock types include granite, gneiss, schist, quartzite, slate, marble, and phyllite. The near-surface material is saprolite, which is composed of clay-rich, unconsolidated material derived from *in situ* weathering of the underlying bedrock. In many valleys, flood plains are underlain by thin, moderate- to well-sorted alluvium deposited by streams. When the distinction between saprolite and alluvium is not important, the unconsolidated material covering the bedrock is generally referred to as regolith.

Near the NIH and NNMC and beneath Wisconsin Avenue in Bethesda, Maryland, the subway system and Medical Center Station and Crossover pass through or beneath the Sykesville Formation (Ꞓs) and the biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite (table 1, fig. 3). The spatially dominant unit is the Sykesville Formation, which is intruded by igneous rocks of various ages. The Red Line tunnel north of the Medical Center Station and Crossover (cross section A–A′) is constructed in the Sykesville Formation. At the Medical Center Station and Crossover (cross section B–B′), the tunnel is in the biotite-hornblende tonalite and south of the Medical Center Station and Crossover (cross section C–C′), the tunnel is constructed in the Sykesville Formation (figs. 3 and 4).

Sykesville Formation

The Sykesville Formation (Ꞓs) is a gneiss that is light to medium gray, lower Cambrian in age, and locally shows a well-developed foliation produced by the alignment of muscovite grains set in a quartzofeldspathic matrix (Fleming and others 1994; Drake 1998). The matrix is composed of quartz, feldspars, and fragments of other metamorphosed rocks (phyllonite, metagraywacke, migmatite, serpentinite, amphibolite, and schist) (Fleming and others, 1994). The spatial organization of the matrix mineralogy imparts a significant mechanical anisotropy to the rock.

There are no exposures of the Sykesville Formation in the vicinity of the Medical Center Station and Crossover, though large exposures within the Washington, D.C. area occur along the banks of the Potomac River in the vicinity

Table 1. *Generalized geologic column for parts of Washington West and Kensington Quadrangles, Washington, D.C., Maryland, and Virginia*

[Modified from Drake, 1998; Fleming and others, 1994; Heath, 1984; Nutter and Otton, 1969]

Not to scale

PERIOD	EPOCH	TIME BEFORE PRESENT (millions of years)	MAP UNIT ON FIGURE 3	SEDIMENT OR ROCK TYPE
Quaternary	Holocene		Qal Q1	Unconsolidated
	Pleistocene	2	Q5	
Tertiary	Miocene	24	T4 Tc	
Ordovician		*unconformity*	Oq Ogl Odt Odl Odm Ok Ogb Ogh Ogg Ogp Ogu Ont Oqu	Igneous intrusives
Ordovician and Cambrian		500	OꞒq Ꞓs	
Cambrian and/or Precambrian		Precambrian older than 570	ꞒZa ꞒZt ꞒZu ꞒZmg ꞒZmp	Metamorphic rocks

of the C & O Canal (fig. 1a). These exposures show a moderately well-developed foliation within the rock mass that does not coincide with the planes of jointing and other fracturing. The dominant joint families are orthogonal to the foliation and cut each other at high angles. Much of the jointing appears to lack a larger-scale three-dimensional interconnectivity (fig. 5).

Biotite-Hornblende Tonalite Member of the Georgetown Intrusive Suite

The biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite that occurs in the vicinity of the Medical Center Station and Crossover is medium- to coarse-grained, early Ordovician in age, and varies from massive to foliated (fig. 3). Fleming and others (1994) reported that the biotite-hornblende tonalite has “strong reflect (igneous) flow structures… and contains many ultramafic and mafic xenoliths, as well as xenoliths of other metasedimentary rocks.” At the Medical Center Station and Crossover area, the biotite-hornblende tonalite is an inclusion or inlier within the larger expanse of the Sykesville Formation (figs. 3 and 4; cross section B–B′). The mean east-west width of this unit is about 1 mile, and within this unit is a smaller north-south elongated inclusion of muscovite-biotite monzogranite (Odl on fig. 3) about 300 ft in width (Fleming and others, 1994). Neither of these igneous bodies is exposed near the Medical Center Station and Crossover.

Outcrops of the biotite-hornblende tonalite can be found along the Potomac River near Lock 8 of the C & O Canal (figs. 1a and 6). Observations of the tonalite and joint orientations at the outcrops indicate that internal fracturing is pervasive. Where foliated, the foliation plane has acted as a plane of weakness, localizing the development of subsequent joints. Orthogonal to this plane, two additional mutually orthogonal planes of joints are well developed. All three planes of jointing are coated with a widespread brown iron-oxide staining, suggesting that paleo-ground-water flow has

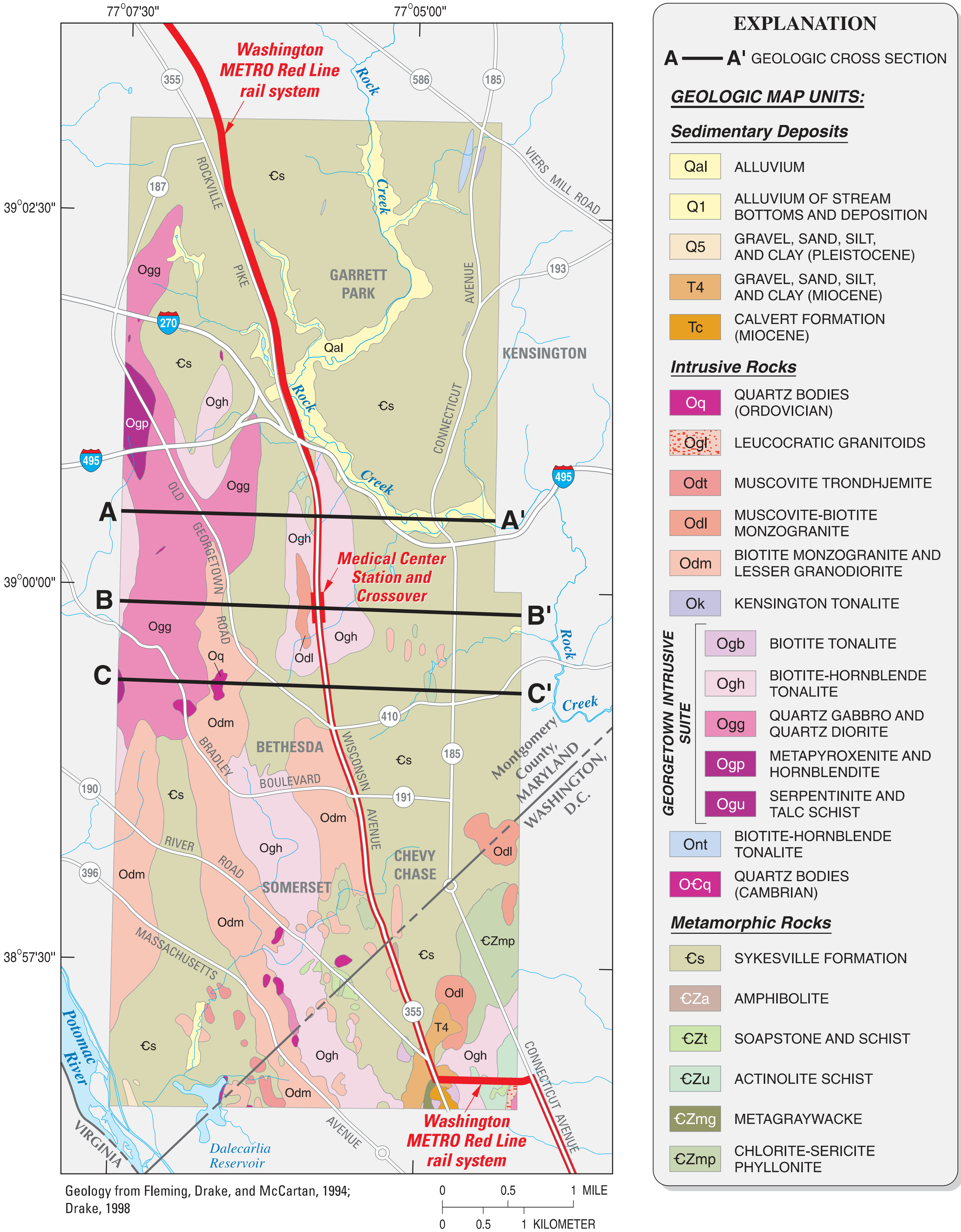


Figure 3. Regional geology near the Medical Center Station and Crossover, Montgomery County, Maryland, and locations of geologic cross sections A-A', B-B', and C-C'.

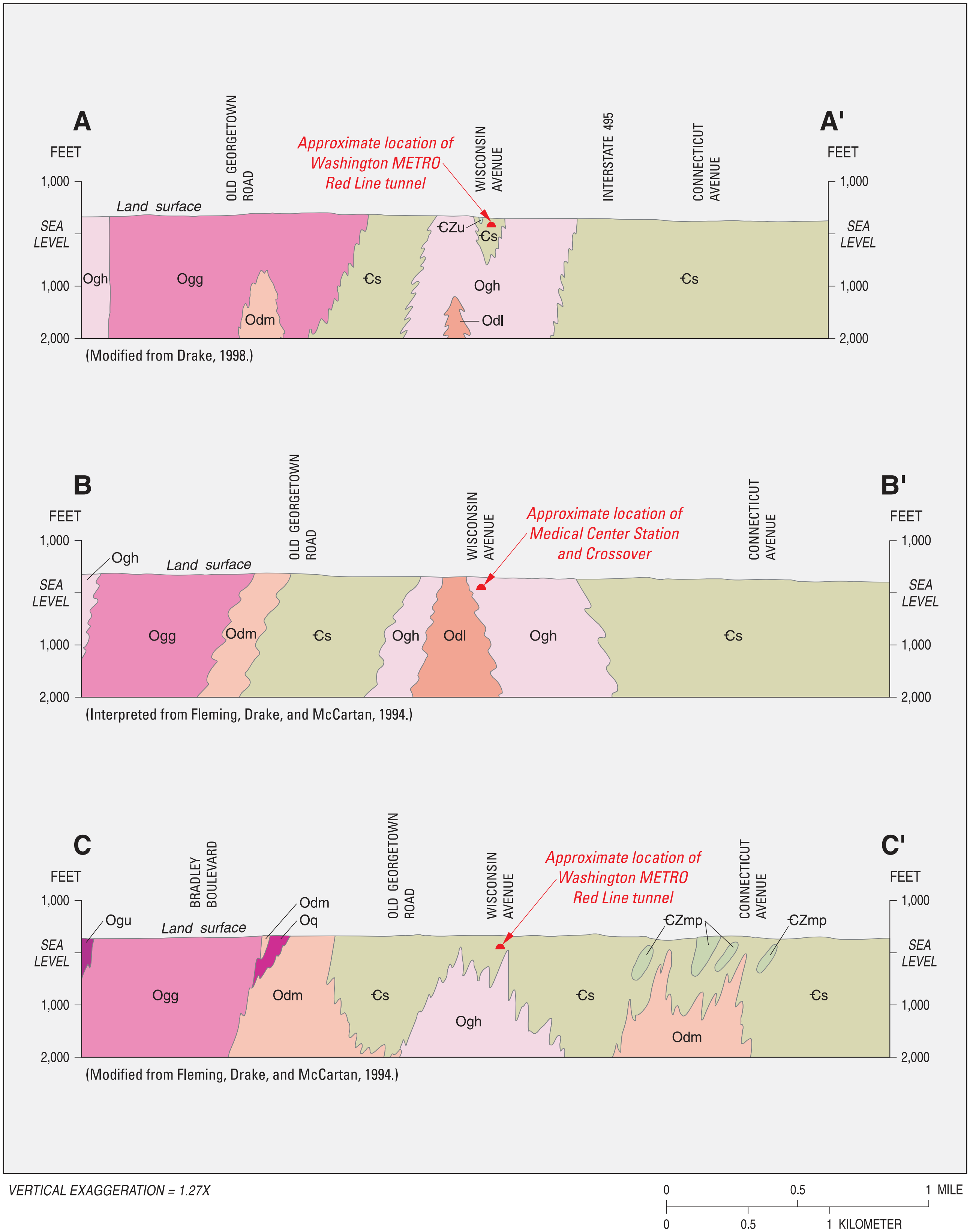


Figure 4. Geologic cross sections A-A', B-B', and C-C'. *(Refer to figure 3 for locations of cross sections and explanation of geologic units.)*

Figure 5. Photographs showing fracture patterns in outcrops of the Sykesville Formation (Ꞓs). *(Refer to figure 1a for location of the outcrops.)*

(A)

(B)

Figure 6. Photographs showing: **(A)** fracture patterns in outcrops of the biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite, and **(B)** seepage of ground water along a fracture. *(Refer to figure 1a for location.)*

taken place. Collectively, the joints define an orthotropic symmetry, and subdivide the rock into a crude boxwork. The geometry of the three joint set populations as well as the observations of actively percolating ground water indicate that an extensive three-dimensional network of fractures has been established in the biotite-hornblende tonalite member of the Georgetown Intrusive Suite.

Structural Controls on Ground-Water Flow

The regional structural geology of the Sykesville Formation (₠s) and biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite may control and influence the direction and magnitude of ground-water flow. Geological structures (foliation, faults, joints, folds, anticlines, and synclines) may be significant hydraulic conductors of ground-water flow if they are connected to form networks of fractures. Planar features (foliation and joints) near the Medical Center Station have been mapped by Fleming and others (1994), Drake (1998), and Drake and Froelich (1997) and are shown in figure 7. The control these planar features have on ground-water flow in the study area is not well defined, although they may be an expression of the fracture orientations and may exert an influence on the direction and rate of ground-water flow in each geologic unit.

Statistical rose diagrams of mapped foliations and joints (146 in the Sykesville Formation and 41 in the biotite-hornblende tonalite) were developed to determine the orientation (direction) of these features. The mapped orientations of the foliation and joints of the Sykesville Formation are generally in a north-south direction with a mean orientation of about 358 degrees and a standard error of plus or minus 10 degrees. In the biotite-hornblende tonalite intrusion, the general orientation of the foliation and joints is shifted 90 degrees to an east-west direction, with a mean orientation of 88 degrees and a standard error of plus or minus 34 degrees (fig. 7).

Hydrogeology

The ground-water-flow system of the Maryland part of the Piedmont and Blue Ridge Region (Heath, 1984) consists of saturated unconsolidated regolith (saprolite, alluvium) overlying saturated fractured bedrock. Regolith will contain water in the pore spaces (intergranular porosity) between the rock particles. The thickness of the regolith ranges from about 30 to 60 ft and can be as thick as 300 ft on some ridge tops, whereas on other ridge tops, the regolith may be very thin or missing and fractured bedrock may be exposed in outcrops. Regolith in the study area can be subdivided between saprolite (deposits on ridges and midslopes) and alluvium (deposits in valleys and streams).

Beneath the regolith is a massive fractured bedrock that has little intergranular porosity, but contains water in permeable fractures (fig. 8). In general, the bulk hydraulic conductivities of the regolith and bedrock are similar and range from about 0.003 to about 3 ft per day (Heath, 1984). The major difference between the regolith and bedrock is porosity, with the regolith having a saturated porosity of about 20 to 30 percent and the bedrock about 0.01 to 2 percent (Heath, 1984).

The saprolite-bedrock contact is a zone of gradation from unconsolidated saprolite (weathered rock) to unweathered fractured bedrock, and is referred to as a transition zone (fig. 8). This transition zone is at the top of the bedrock and although it may not be geologically different from the fractured bedrock, it may be acting very differently hydraulically because of the extensive clay infilling of the fractures. The clay infilling of fractures may lower the hydraulic conductivity and slow vertical leakage from the unconsolidated saprolite to the unweathered fractured bedrock.

In general, ground water will move as in a typical regional flow system, from recharge in the topographic highs (ridges) to discharge in areas of topographic lows (streams and valleys). Depending on location, the bedrock may receive areal recharge from the regolith and may also discharge water to the regolith. Ground-water systems function as reservoirs (storage of water) and as conduits that transmit water from recharge areas to discharge areas. The ground-water system in the Piedmont can be viewed as two separate and interconnected flow systems (regolith and bedrock), because of their difference in storage (porosity) (fig. 8). Because of its larger porosity, the regolith can be considered to be a reservoir that slowly feeds water into the lower bedrock fractures. The fractures act as a network of conduits that transmit water to wells, springs, or openings in the bedrock, such as tunnels.

Saprolite

Bedrock at the Medical Center Station and Crossover is covered by saprolite. The saprolite (approximately 20–55 ft thick) is a soft, red/brown to gray, earthy, weathered porous material formed from decomposed crystalline rock in which constituent minerals, other than quartz, have been altered to clays. Permeability of the saprolite is variable, but commonly is highest just above the unweathered bedrock (Nutter and Otton, 1969). The upper part of the saprolite is generally a few feet thick, massive, and grades upward into a soil. As the saprolite grades downward, it retains the structural characteristics of the unweathered bedrock. At the saprolite-bedrock contact is a transition zone, whose thickness is highly variable.

Engineering consultants for WMATA (DMJM/Deleuw, Cather & EBA Engineering, Inc., 2001) performed surface geophysical investigations near the Medical Center Station and Crossover area to determine the thickness of the saprolite and explore any unconformities in the saprolite-bedrock contact, which might indicate preferential pathways (faults, joints, folds) for ground-water flow. The location of seismic refraction lines and 2-D resistivity lines is shown in figure 9. The seismic-refraction profiles show that near the Medical Center Station and Crossover, the saprolite thickness ranges from 20–55 ft and the 2-D resistivity profiles identified several possible anomalies in the saprolite-bedrock contact that may indicate areas of intensive fracturing (DMJM/

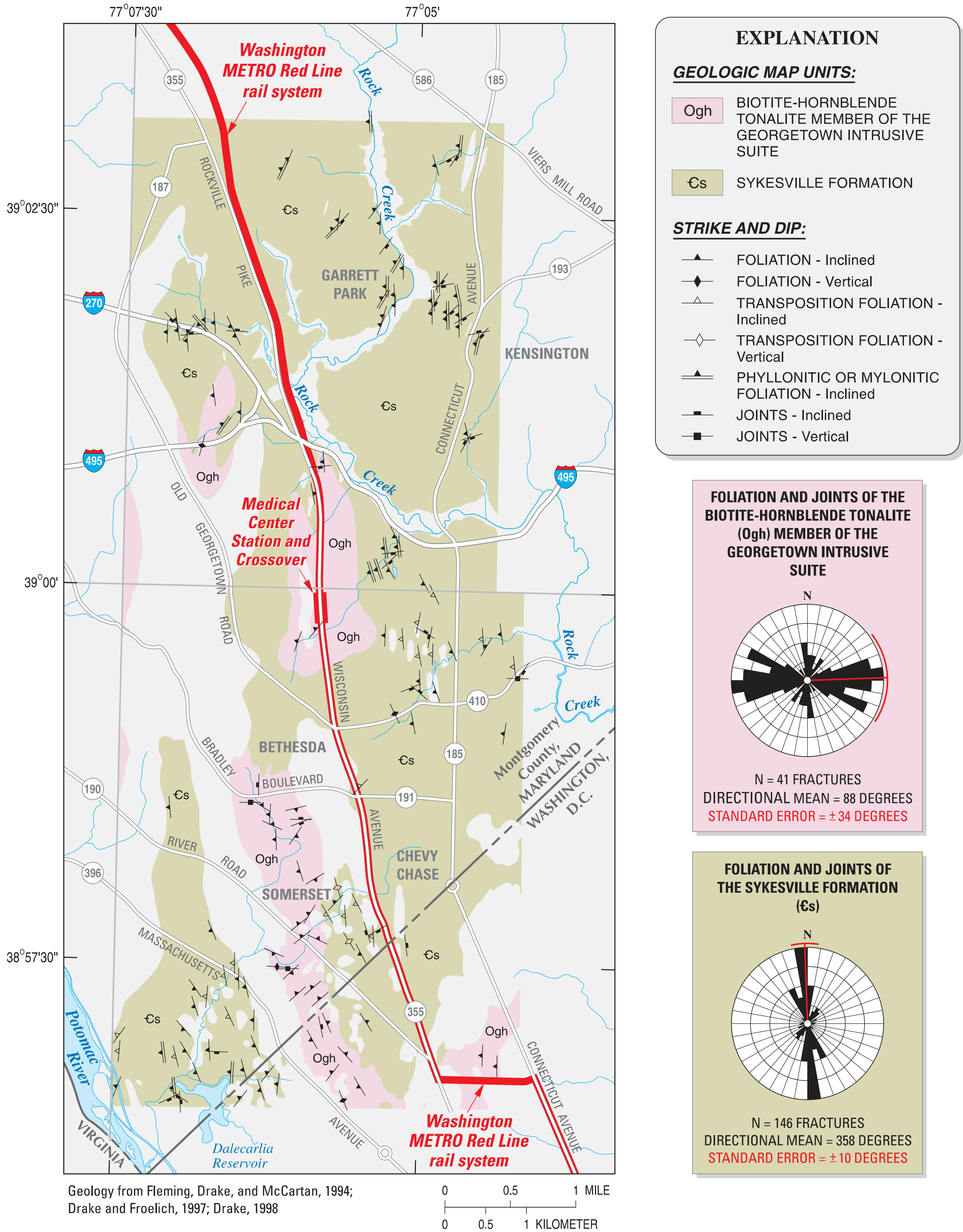


Figure 7. Geologic map and orientation of foliation and joints in the Sykesville Formation (Ꞓs) and the biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite.

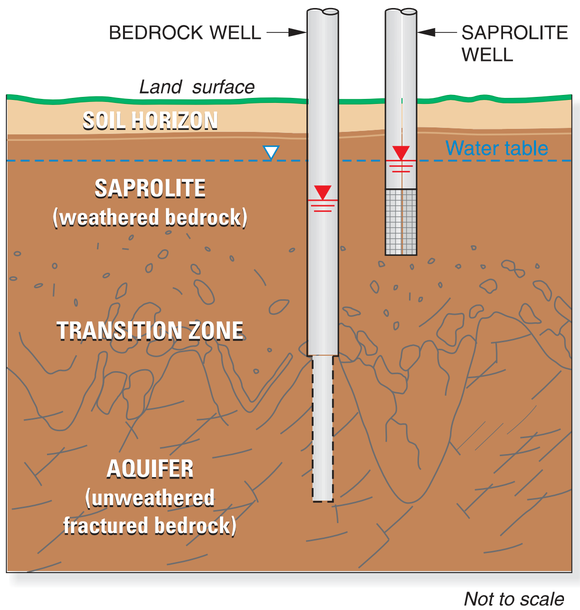


Figure 8. Conceptual hydrologic model for the Piedmont Region showing a water table in the saprolite and relative hydraulic heads in bedrock and saprolite wells.

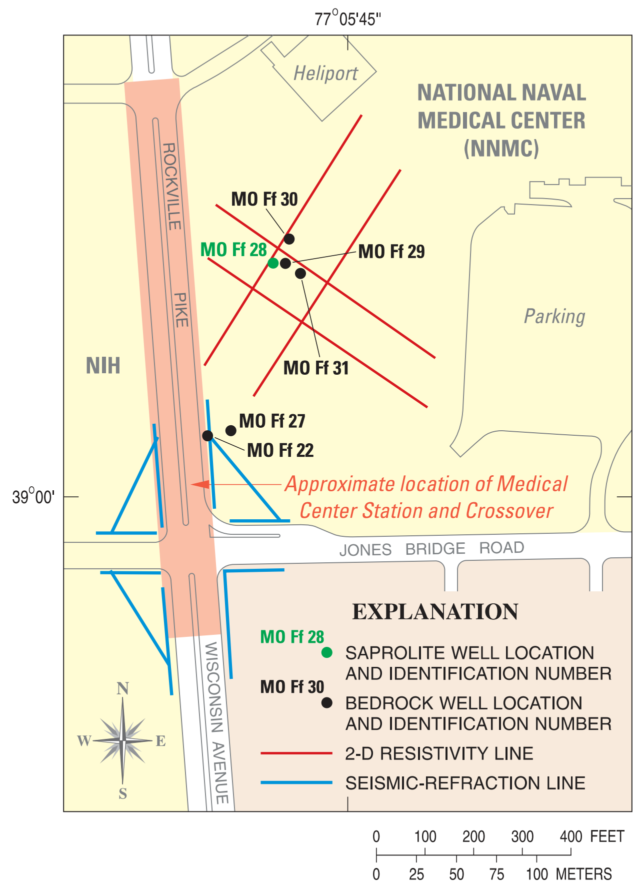


Figure 9. Location of National Naval Medical Center well field, seismic-refraction lines, and 2-D resistivity lines.

Deleuw, Cather & EBA Engineering, Inc., 2001). Test wells (MO Ff 29, MO Ff 30, and MO Ff 31) were located and drilled based on the information from the seismic refraction and 2-D resistivity geophysical surveys.

Two observation wells (MO Eg 28 and MO Ff 28) near the Medical Center Station and Crossover are finished in the saprolite. Well-construction data for these wells are listed in table 2 and the locations are shown in figures 9 and 10. Well MO Eg 28 (fig. 10) is an existing saprolite monitoring well with a 25-ft screen. MO Ff 28 (fig. 9) was drilled as part of this study and has a 10-ft screen in the lower part of the saprolite.

Response of water levels in the saprolite to precipitation at well MO Eg 28 is shown in figure 11. The hydrograph is fairly constant for the period of record, even though significant rainfall events were recorded for several months (May–August) at the nearby National Oceanic and Atmospheric Administration (NOAA) Station 2325 (Dalecarlia Reservoir, Washington, D.C.). Based on the hydrograph (fig. 11), water levels in the saprolite at this site do not have a strong response to recharge. This is probably because porosity and storage capacity in the saprolite are very high. The high storage capacity of the saprolite is essentially keeping it fully saturated, and the response to recharge and droughts is minor.

An air-pressurized slug test (Shapiro and Greene, 1995; Greene and Shapiro, 1995) was conducted in observation well MO Ff 28 to estimate transmissivity, hydraulic conductivity, and storativity of the saprolite. This type of test only stresses a limited volume (few feet) of geologic material around the well. The data were analyzed graphically and transmissivity (T) is 10 ft^2/d (feet squared per day), hydraulic conductivity (K) is 1 ft/d (foot per day), and storativity (S) is 10^{-6} (fig. 12).

Bedrock Aquifer

The hydraulic properties of the fractured bedrock aquifer are controlled by the fractures; therefore, a detailed knowledge of the geometric and hydraulic properties of the fractures is required to characterize the ground-water-flow system. Test wells were drilled into the biotite-hornblende tonalite (Ogh, on fig. 3) member of the Georgetown Intrusive Suite at the NNMC, adjacent to the Medical Center Station and Crossover, to determine the hydraulic properties of the fractured bedrock (fig. 9). Characteristics of the fractures in the bedrock were investigated using borehole-geophysical logging techniques. These techniques can be used to infer the location and orientation of fractures intersecting the borehole. The hydraulic properties of the fractures were determined using single-hole and multiple-hole hydraulic tests. Hydraulic heads measured in the bedrock boreholes

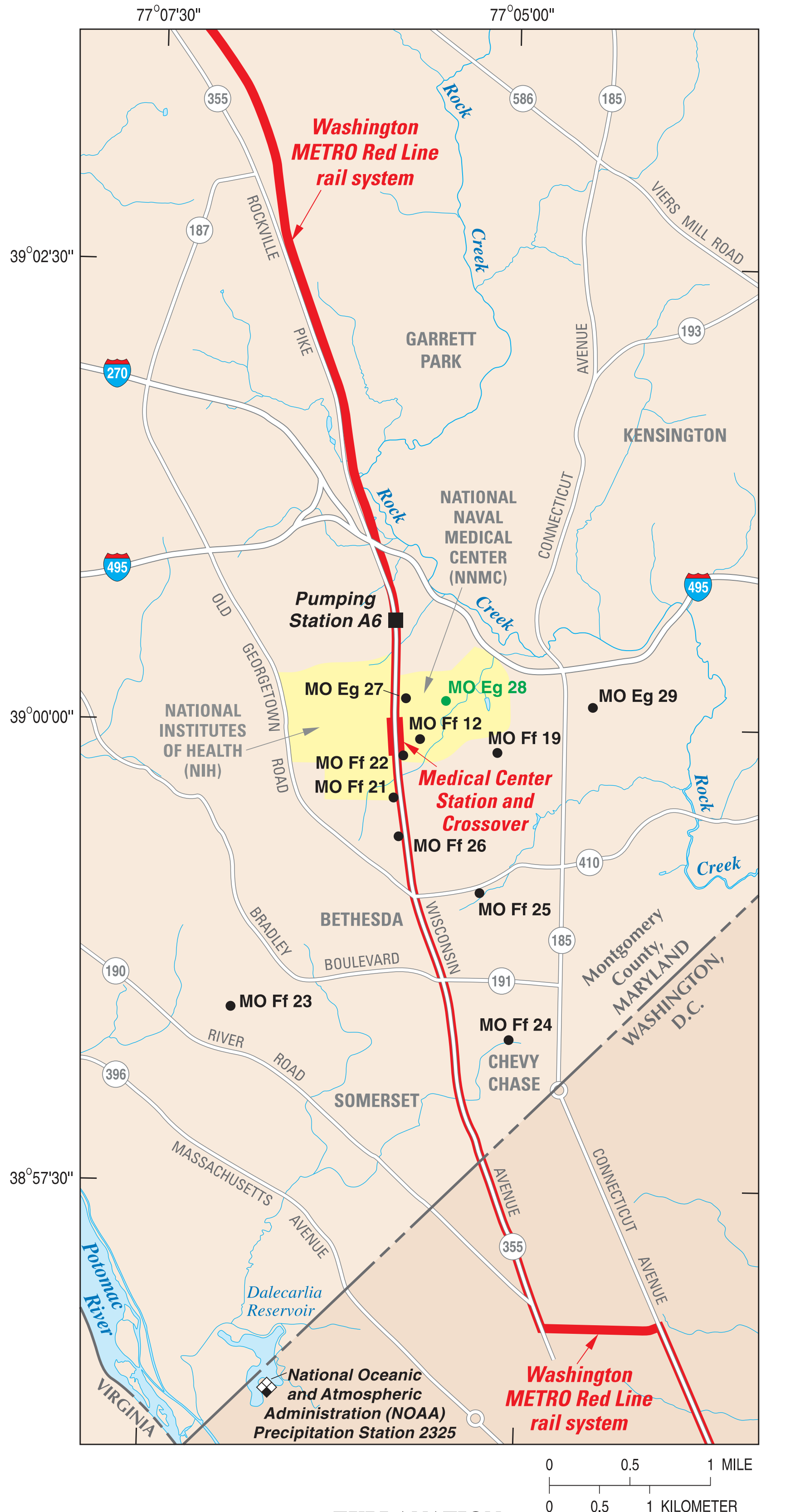
Table 2. *Data for wells used for borehole geophysics, water-level measurements, and aquifer testing*

[Location of wells shown in figures 9 and 10; °, degree; ', minute ; ", second; msl, mean sea level; --, no data]

U.S. Geological Survey well number	State of Maryland well permit number/ identification	Owner	Latitude (° ' ")	Longitude (° ' ")	Altitude of land surface, (feet msl)	Casing depth (feet)
MO Eg 27	AM-41U	WMATA [1]	39 00 08	77 05 48	268.9	147
MO Eg 28	MO-94-0540	NNMC [2]	39 00 08	77 05 27	301.1	15
MO Eg 29	MO-81-2116	Private	39 00 07	77 04 26	281.2	38
MO Ff 12	--	NNMC	38 59 56	77 05 37	274.4	--
MO Ff 19	MO-69-0225	CCC [3]	38 59 52	77 05 08	322.8	30
MO Ff 21	A-74	WMATA	38 59 37	77 05 47	329.9	132
MO Ff 22	A-79	WMATA	38 59 51	77 05 47	320.7	137
MO Ff 23	MO-73-3188	KGC [4]	38 58 28	77 06 53	342.4	43
MO Ff 24	MO-93-0418	CCCC [5]	38 58 19	77 04 58	307.5	24
MO Ff 25	MO-92-0268	RCC [6]	38 59 08	77 05 12	323.0	24
MO Ff 26	A-71	WMATA	38 59 25	77 05 43	352.0	147
MO Ff 27	MO-94-1755	WMATA	38 59 51	77 05 47	328.0	60
MO Ff 28	MO-94-1759	WMATA	38 59 55	77 05 45	318.9	35
MO Ff 29	MO-94-1762	WMATA	38 59 55	77 05 45	318.9	60
MO Ff 30	MO-94-1757	WMATA	38 59 55	77 05 45	315.7	60
MO Ff 31	MO-94-1756	WMATA	38 59 55	77 05 45	322.0	60
A6 [7]	--	WMATA	39 00 39	77 05 51	260.0	--

U.S. Geological Survey well number	Length of open hole (feet)	Total depth (feet)	Thickness of overburden (feet)	Year drilled	Lithology	Type of well
MO Eg 27	3	150	25	1974	Bedrock	Observation
MO Eg 28	25	40	28	1998	Saprolite	Observation
MO Eg 29	162	200	14	1998	Bedrock	Water Supply
MO Ff 12	--	275	--	1951	Bedrock	Water Supply
MO Ff 19	125	155	35	1961	Bedrock	Irrigation
MO Ff 21	3	135	25.5	1970	Bedrock	Observation
MO Ff 22	3	140	45.5	1970	Bedrock	Observation
MO Ff 23	457	500	10	1981	Bedrock	Irrigation
MO Ff 24	276	300	5	1995	Bedrock	Irrigation
MO Ff 25	20	44	35	1992	Bedrock	Observation
MO Ff 26	3	150	41	1970	Bedrock	Observation
MO Ff 27	91.5	151.5	34.3	2001	Bedrock	Observation
MO Ff 28	10	45	--	2001	Saprolite	Observation
MO Ff 29	180	240	45	2001	Bedrock	Observation
MO Ff 30	180	240	50	2001	Bedrock	Observation
MO Ff 31	180	240	55	2001	Bedrock	Observation
A6	--	--	--	--	--	Pump Station

[1] Washington Metropolitan Area Transit Authority
[2] National Naval Medical Center
[3] Columbia Country Club
[4] Kenwood Golf Club
[5] Chevy Chase Country Club
[6] Riviera of Chevy Chase
[7] Pumping Station for the Medical Center Area



EXPLANATION

MO Ff 24 ● WELL LOCATION IN BEDROCK AND IDENTIFICATION NUMBER (Refer to table 2.)

MO Eg 28 ● PIEZOMETER LOCATION IN SAPROLITE AND IDENTIFICATION NUMBER

Figure 10. Location of regional wells, National Oceanic and Atmospheric Administration (NOAA) precipitation station 2325, and pumping station A6.

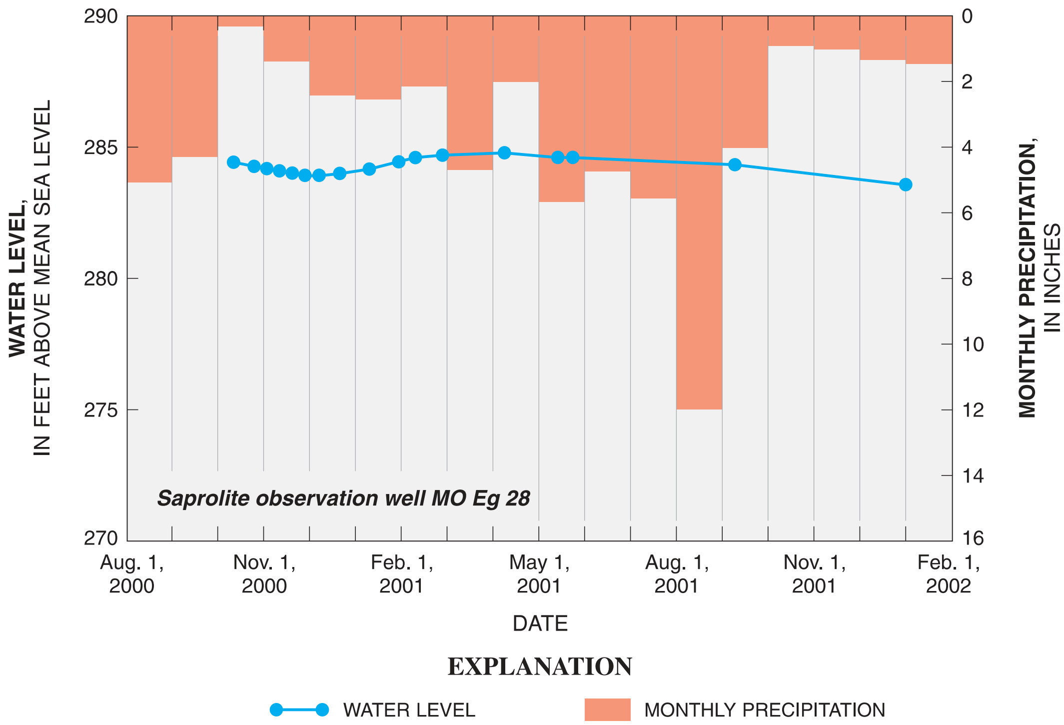


Figure 11. Hydrograph for saprolite observation well MO Eg 28 *(fig. 10)* and monthly rainfall hyetograph for National Oceanic and Atmospheric Administration (NOAA) precipitation station 2325 at Dalecarlia Reservoir in Washington, D.C.

were used to infer the hydraulic gradients in the bedrock and the direction of ground-water flow. In addition, sources and sinks of water to the bedrock were investigated by considering responses in saprolite and bedrock wells to precipitation and ground-water discharge measured at pumping station A6 (fig. 10).

Response of water levels in the bedrock to precipitation measured at nearby NOAA Station 2325 (Dalecarlia Reservoir, Washington, D.C.) observation well MO Eg 27 is shown in figure 13. Water levels in the bedrock are very responsive to recharge and drought because the bedrock does not have the high porosity or storage capacity of saprolite. The introduction of recharge to the bedrock can result in large changes of fluid pressure in the bedrock.

Bedrock Boreholes Four 6-inch bedrock test wells (MO Ff 27, MO Ff 29, MO Ff 30, and MO Ff 31) and one 2-inch saprolite test well (MO Ff 28) were drilled for this investigation using an air-rotary drilling method (fig. 9). The bedrock wells were drilled through the unconsolidated material and/or weathered rock to about 5 ft into competent rock. Casing was set through the saprolite and/or weathered rock and grouted into the competent bedrock. The bedrock was then drilled as an open hole to about 240 ft below land surface for boreholes MO Ff 29, MO Ff 30, and MO Ff 31 and to a depth of about 150 ft below land surface for

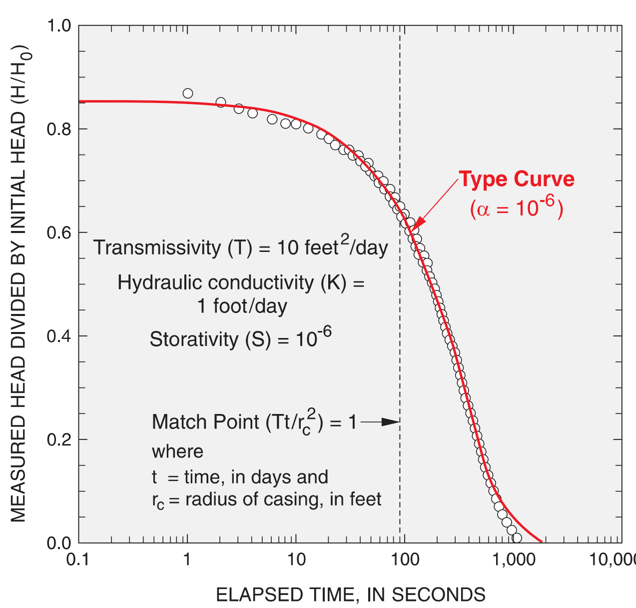


Figure 12. Best-fit type-curve match to the drawdown data from the air-pressurized slug test conducted in observation well MO Ff 28, using an applied air pressure of 3.8 pounds per square inch.

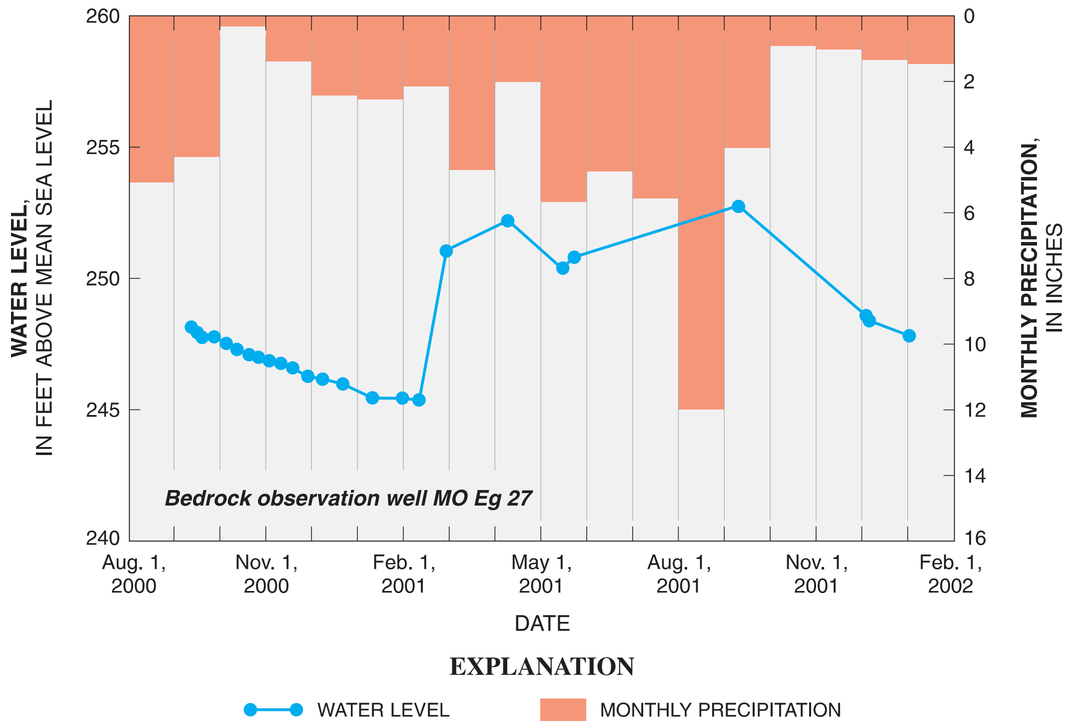


Figure 13. Hydrograph for bedrock observation well MO Eg 27 *(fig. 10)* and monthly rainfall hyetograph for National Oceanic and Atmospheric Administration (NOAA) precipitation station 2325 at Dalecarlia Reservoir in Washington, D.C.

MO Ff 27. In addition, drill cuttings were collected and inspected to help define the lithology of the bedrock. Geophysical logs from the boreholes are shown in figures 14–17. To assist with interpretation, the driller’s log and the water-bearing zones (fractures that produce water) from the on-site driller’s reports are included for each well. Generally, water-bearing zones in each well were limited, and found mostly in the biotite-hornblende tonalite where biotite was dominant. Even though there are numerous fractures in the hornblende-biotite, the driller did not report significant water production in these fractures (figs. 14–17). Well MO Ff 29 (fig. 15) was drilled into mostly hornblende-biotite and had the least amount of water compared to the other wells. Wells MO Ff 27, MO Ff 30, and MO Ff 31 all had zones where biotite dominated and all these wells produced significant amounts of water (figs. 14–17).

Borehole Geophysics Geophysical well logs are an important tool in characterizing aquifers. Geophysical logs provide a continuous depth sampling record of undisturbed material that can be associated with numerous types of measurements (Keys and MacCary, 1981; Paillet and Crowder, 1996). Geophysical-logging surveys of the wells at the NNMC site (fig. 9) included: caliper, natural gamma, resistivity, short- and long-normal resistivity, and acoustic televiewer.

The acoustic televiewer logs were used in each well to map the fractures intersecting the boreholes. Fracture location and orientation (strike and dip) were identified in each borehole (figs. 14–17). This information was used to compare to the regional fracture statistics for the Sykesville Formation and biotite-hornblende tonalite member of the Georgetown Intrusive Suite. In addition, the information obtained by the acoustic televiewer logs was also used to determine where to conduct single-hole hydraulic tests within the borehole. The east-west strike of the fractures in the boreholes is nearly in the same direction as the regional distribution of structural features mapped for the biotite-hornblende tonalite (fig. 18). The dip of the fractures (angle of inclination from horizontal) determined from the acoustic televiewer logs shows that they are steeply dipping with a mean dip angle of about 65 degrees (fig. 19).

Hydraulic Heads and Hydraulic Gradients The Bethesda area of Montgomery County, Maryland, is highly urbanized and much of the water supplied for business and private residences is provided by city water utilities. Therefore, only a few wells in the bedrock were available to develop an areal bedrock hydraulic head map in the Medical Center Station and Crossover area (table 2, fig. 20). Even though there are very few head measurements for the bedrock, a hydraulic head map is approximated for most of the study

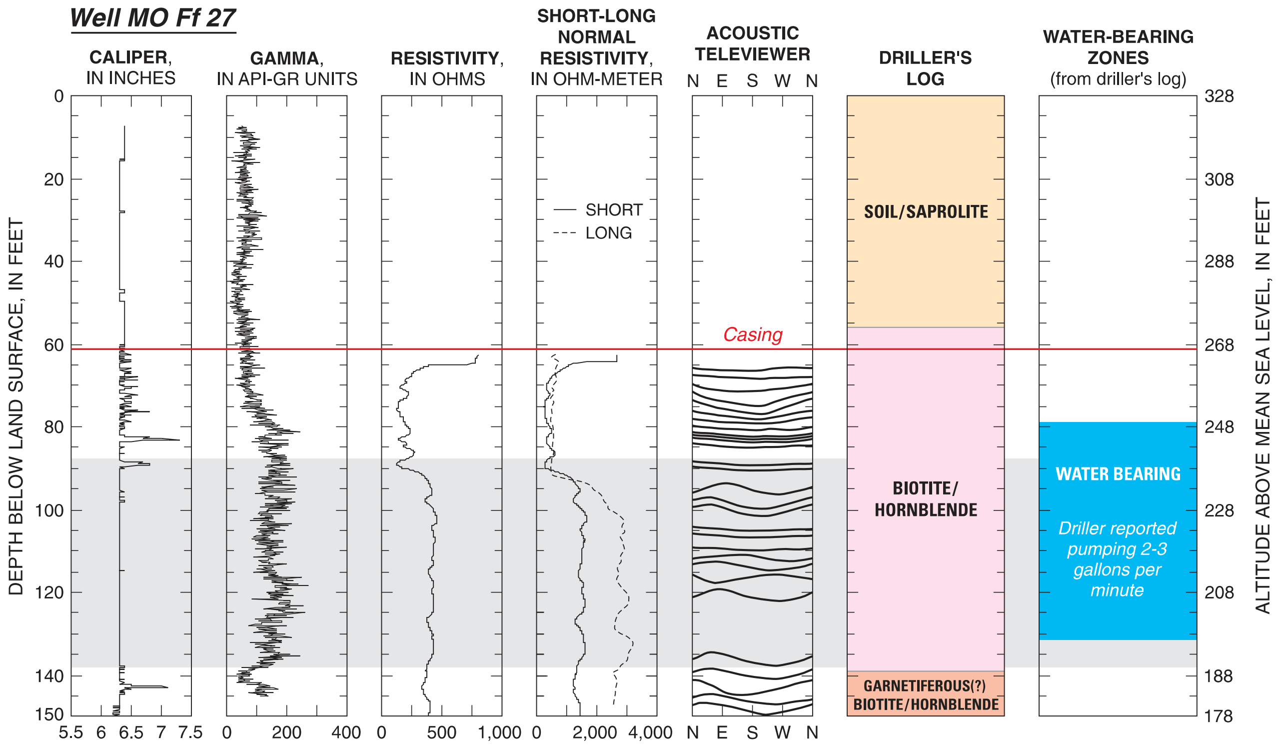


Figure 14. Selected geophysical and driller's logs for well MO Ff 27.

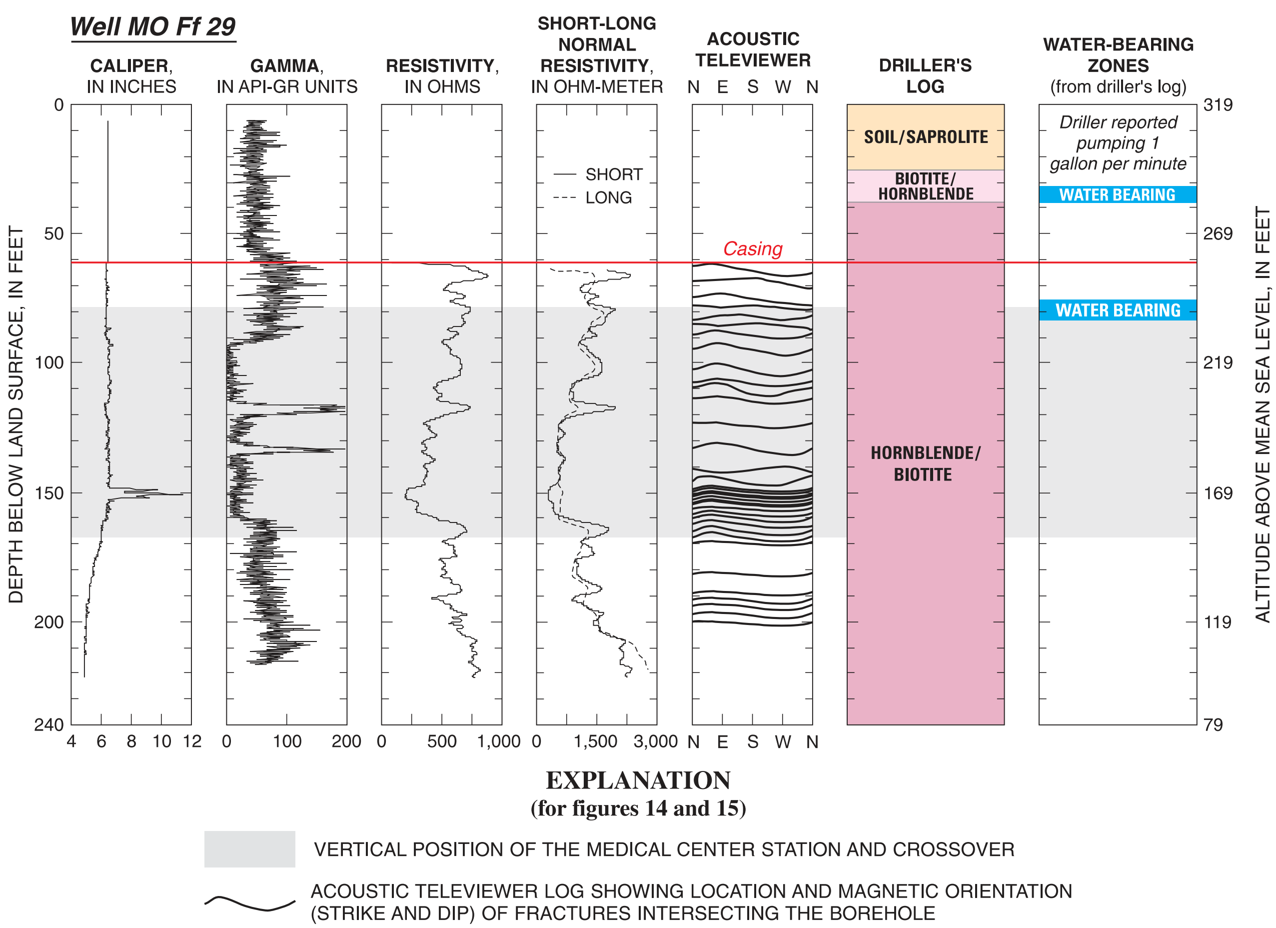


Figure 15. Selected geophysical and driller's logs for well MO Ff 29.

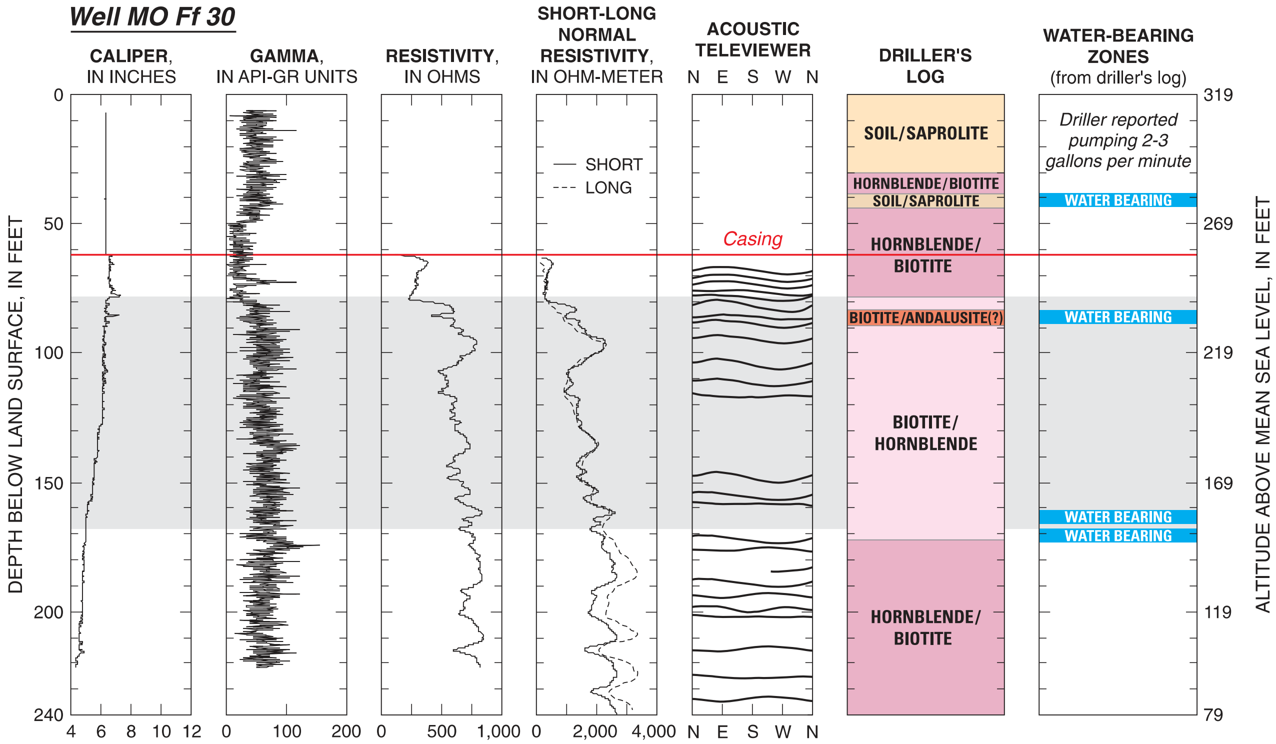
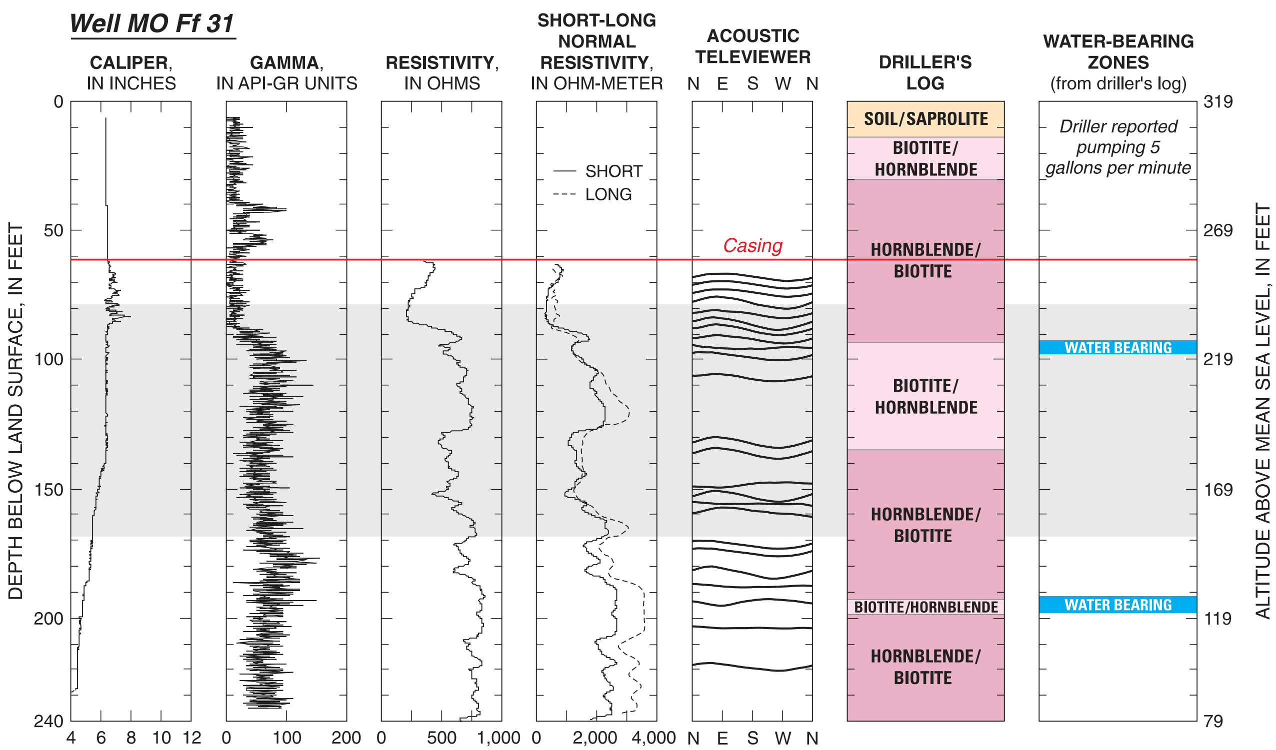


Figure 16. Selected geophysical and driller's logs for well MO Ff 30.



EXPLANATION
(for figures 16 and 17)

VERTICAL POSITION OF THE MEDICAL CENTER STATION AND CROSSOVER

ACOUSTIC TELEVIEWER LOG SHOWING LOCATION AND MAGNETIC ORIENTATION (STRIKE AND DIP) OF FRACTURES INTERSECTING THE BOREHOLE

Figure 17. Selected geophysical and driller's logs for well MO Ff 31.

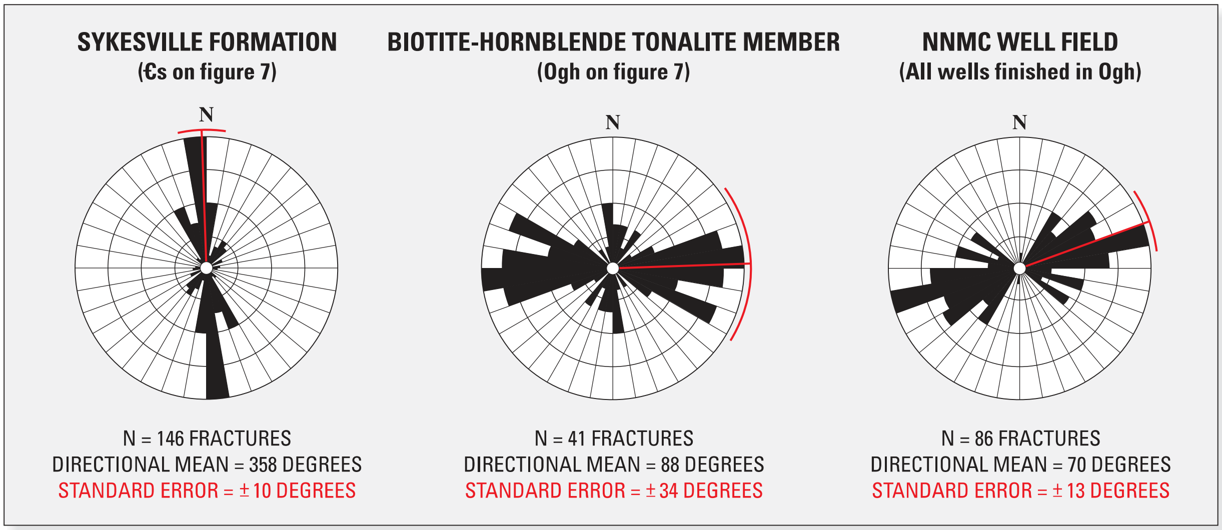


Figure 18. Orientation of mapped foliation and joints in the Sykesville Formation (Ꞓs) and biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite, and fracture orientations in wells at the National Naval Medical Center (NNMC) well field. *(Data from Fleming and others, 1994; Drake, 1998.)*

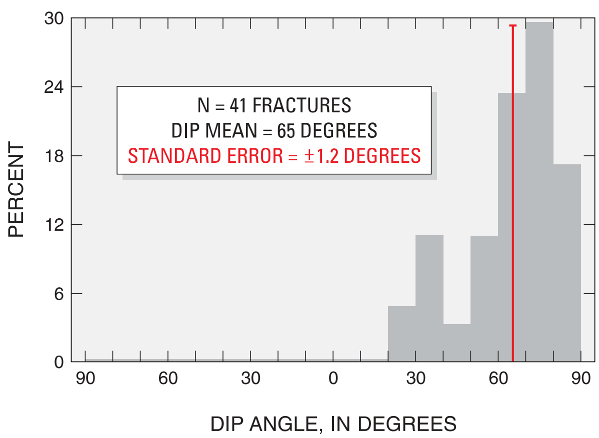


Figure 19. Histogram and statistics (mean and standard error) of the dip of the fractures mapped by the acoustic televiewer in wells at the National Naval Medical Center (NNMC) well field.

area (fig. 20). Heads measured in the bedrock provide insight into areal ground-water flow. The general direction of ground-water flow is from the drainage divides to minor streams and Rock Creek at lower elevations. The hydraulic heads are approximated on the west side of the Red Line due to the sparse number of bedrock wells. The Medical Center Station and Crossover and adjacent tunnel act as a drain, routing ground-water flow into the subway.

The abrupt directional change in ground-water flow at the contact between the Sykesville Formation and the biotite-hornblende tonalite may be a result of different fracture orientations in these units. In addition, it is likely that the east-west oriented fractures in the biotite-hornblende tonalite may intersect the north-south oriented Medical Center Station and Crossover and tunnel with a high frequency, resulting in increased water intrusion into the tunnel.

Single-hole hydraulic tests were conducted in hydraulically isolated intervals in observation wells MO Ff 27, MO Ff 29, MO Ff 30, and MO Ff 31 at the NNMC site using equipment described in Shapiro (2001). Prior to conducting each single-hole test, the ambient hydraulic head was measured (fig. 21). The ambient hydraulic head in the open borehole is a composite hydraulic head; the hydraulic head associated with each fracture may differ from the open hole hydraulic head because of the local hydrologic conditions and the connectivity of the fractures (Shapiro, 2002). Information about the variability of the hydraulic head in fractures over the length of the borehole is important in understanding the local flow regime in the fractured bedrock.

The estimate of the ambient hydraulic head in each test interval was made using a fluid-pressure transducer placed

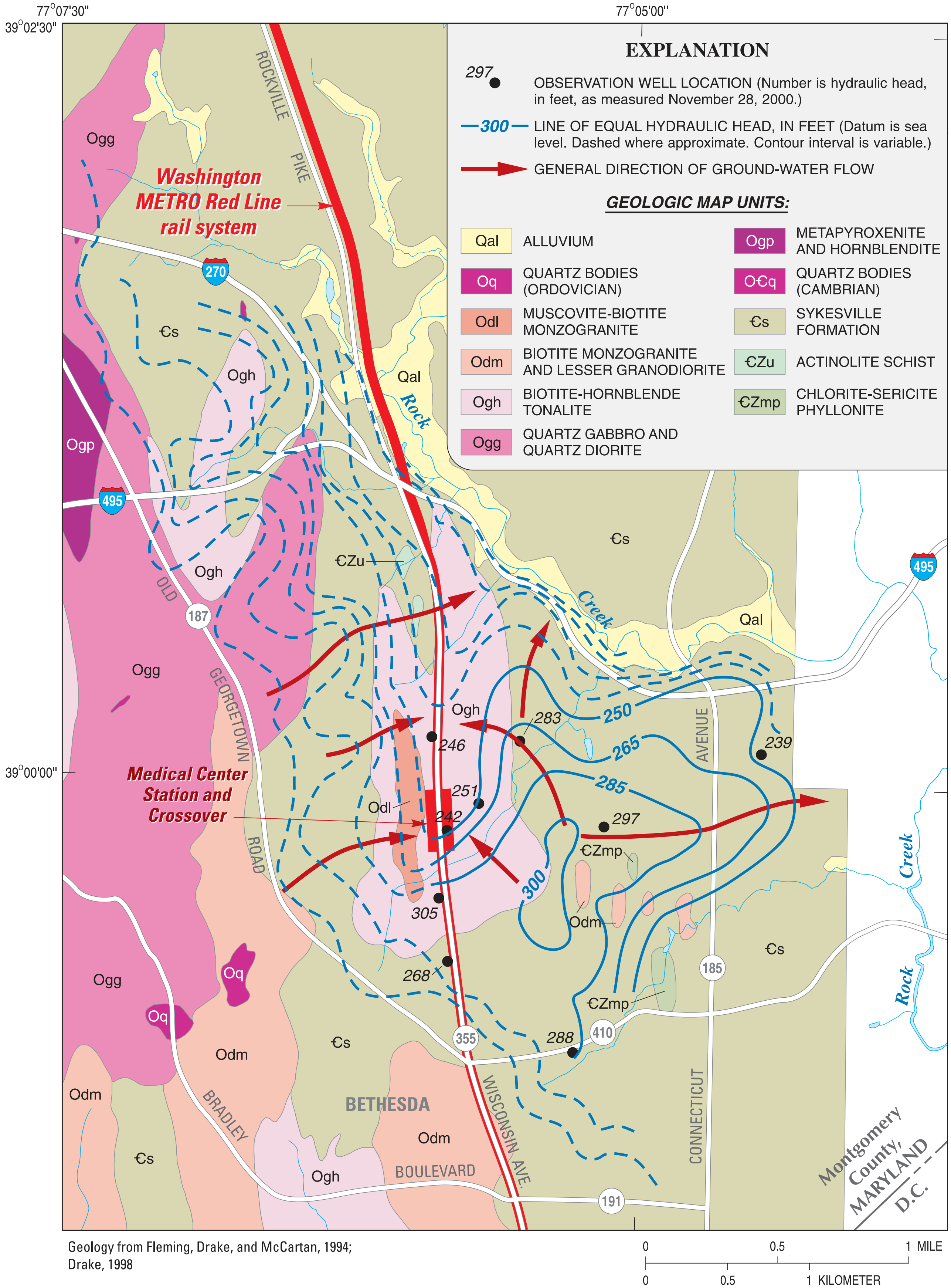


Figure 20. Regional hydraulic heads in the bedrock (measured November 28, 2000) and general direction of ground-water flow.

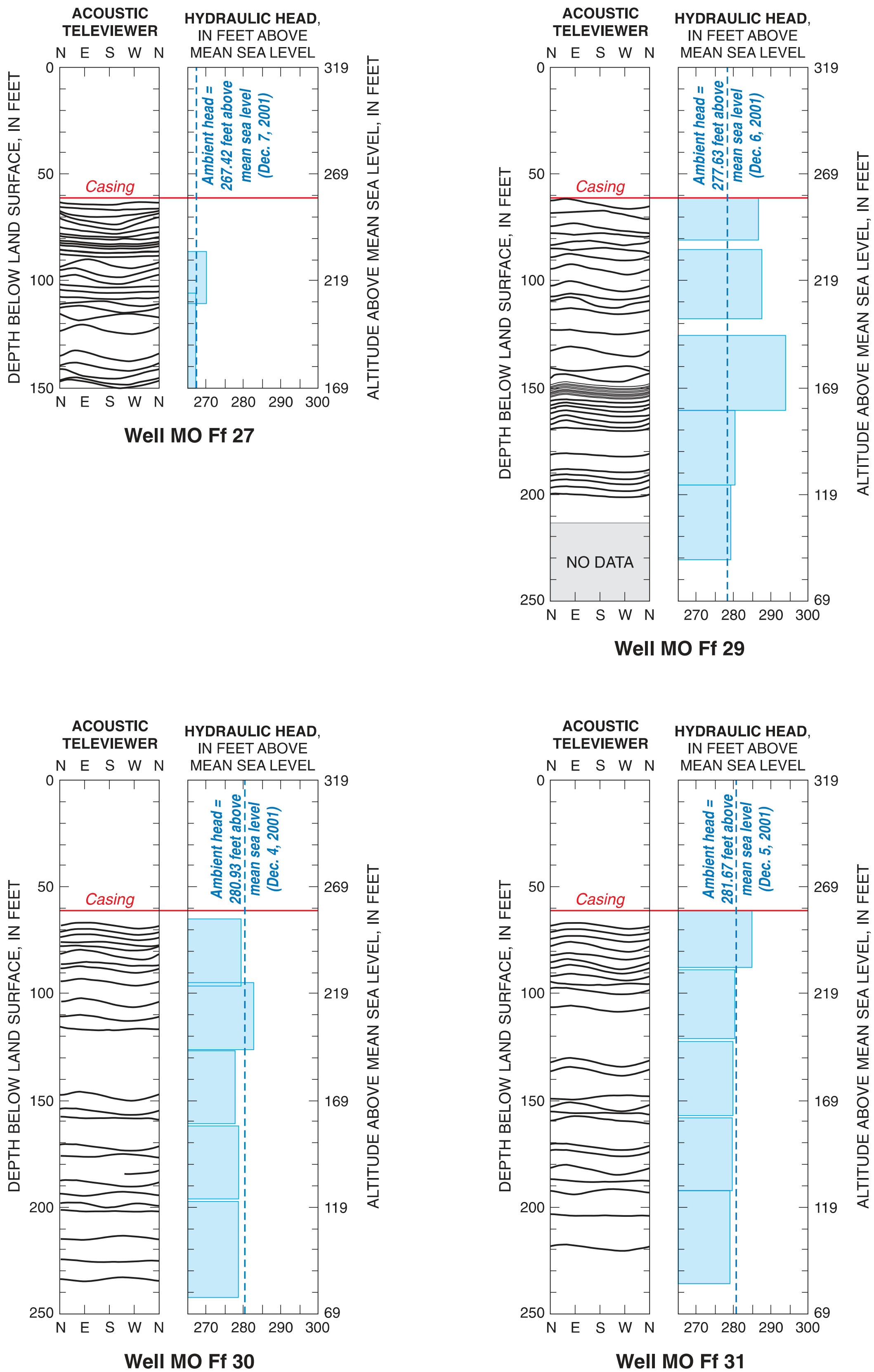


Figure 21. Hydraulic head determined from packer tests in National Naval Medical Center (NNMC) wells MO Ff 27, MO Ff 29, MO Ff 30, and MO Ff 31.

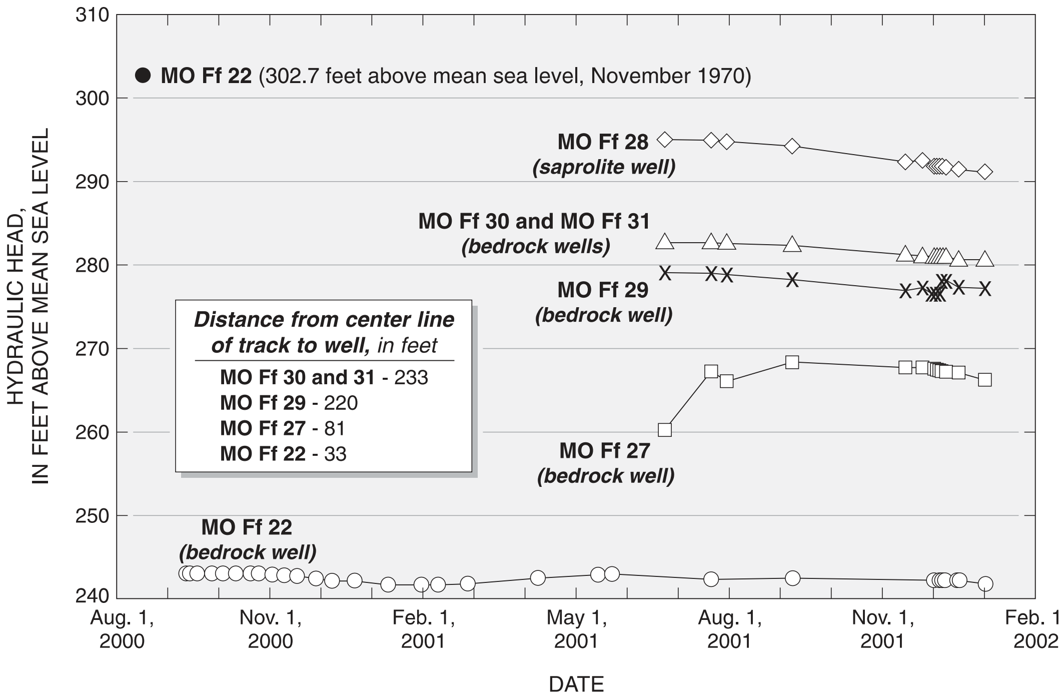


Figure 22. Hydrograph for saprolite observation well MO Ff 28 and open bedrock observation wells MO Ff 22, MO Ff 27, MO Ff 29, MO Ff 30, and MO Ff 31 at the National Naval Medical Center (NNMC) well site.

in the test interval of the apparatus. After inflating the two borehole packers to isolate the section of the borehole for a single-hole fluid-injection test, the fluid pressure was allowed to equilibrate prior to initiating the fluid-injection test. The hydraulic head in the test interval prior to the start of the fluid-injection test is assumed to represent the ambient hydraulic head in the test interval. The length of the test interval where the hydraulic head was measured is shown in figure 21.

In general, hydraulic head decreases with depth in bedrock wells MO Ff 29, MO Ff 30, and MO Ff 31, indicating the potential for downward ground-water flow. The potential for downward ground-water flow implies that the water in the saprolite is recharging the bedrock aquifer. The hydraulic head in saprolite well MO Ff 28 at the NNMC is higher than in wells MO Ff 29, MO Ff 30, and MO Ff 31 (fig. 22), which further indicates that ground water is flowing downward from the saprolite to the bedrock.

The hydraulic head in the upper three test intervals below the bottom of the surface casing in well MO Ff 29 appears to be unusually high in comparison to the hydraulic head at similar elevations in wells MO Ff 30 and MO Ff 31. This is likely the result of not allowing the hydraulic head in the test interval to equilibrate for a sufficient period of time prior to conducting the single-hole fluid-injection test; the time required to achieve the ambient hydraulic head in test intervals with low transmissivity is longer than in high-transmissivity test intervals.

Hydraulic heads in well MO Ff 27 also showed potential for downward ground-water flow in the bedrock. The lower hydraulic heads with depth in this borehole show that hydraulic head in this well is greatly affected by the nearby subway tunnel. The hydraulic head is more than 10 ft lower in well MO Ff 27 than at similar elevations in wells MO Ff 29, MO Ff 30, and MO Ff 31 (fig. 22). The atmospheric pressure in the subway tunnel causes the gradient in the hydraulic head in the bedrock to be in the direction of the tunnel. Thus, the hydraulic heads measured in the test intervals of MO Ff 27 cannot be interpreted as only showing the potential for downward ground-water flow. Additional wells in the vicinity of the subway tunnel would be needed to provide more detail on the nature of the hydraulic gradient and the directions of ground-water flow in the vicinity of the subway tunnel. The hydraulic heads in the bedrock observation well MO Ff 22 (33 ft from the tunnel) are about 50 ft lower than hydraulic heads in well MO Ff 27 (81 ft from the tunnel) (fig. 22).

Hydraulic Properties of the Bedrock Aquifer The ease with which water moves through a geologic material is defined by the formation transmissivity (Bear, 1979). Estimates of transmissivity are made by conducting hydraulic tests in which a known hydraulic perturbation is imposed by either injecting or withdrawing water while measuring the associated fluid pressure response. *In situ* hydraulic tests can be conducted in a single borehole, where the hydraulic perturbation and pressure response are measured in the same borehole, or in multiple boreholes, where the pressure response to the hydraulic perturbation is measured at multiple locations. Single-hole hydraulic tests in bedrock aquifers are usually conducted for short durations (minutes to hours) to infer the transmissivity of the fractures in the immediate vicinity of the borehole being tested, and provide insight into the range and spatial variability of hydraulic properties of fractures in the bedrock. Multiple-hole tests are often conducted over longer durations than single-hole tests (hours to days) to infer the bulk transmissivity over much larger volumes of rock. This bulk transmissivity in bedrock aquifers is of significance in understanding the ease with which water can move through complex networks of interconnected fractures. Single-hole and multiple-hole hydraulic tests were conducted at the bedrock wells installed in the vicinity of the Medical Center Station and Crossover (fig. 9).

Single-Hole Hydraulic Tests Single-hole hydraulic tests were conducted using the apparatus described in Shapiro (2001). In general, the apparatus consists of two inflatable borehole packers that can form a hydraulic seal against the borehole wall to isolate a short section of a bedrock borehole (the test interval) for either fluid injection or pumping. Fluid-injection tests, as described in Shapiro and Hsieh (1998), were conducted in bedrock wells MO Ff 27, MO Ff 29, MO Ff 30, and MO Ff 31. The test apparatus was set up with borehole packers separated by 33.78 ft. The fluid-injection rate and the associated increase in fluid pressure were measured in the test interval. The transmissivity of the test interval was estimated using a steady-state flow approximation (Shapiro and Hsieh, 1998). The fluid pressure response above and below the test interval in the borehole was also monitored during fluid-injection tests to ensure that borehole packers formed suitable hydraulic seals against the borehole wall.

The estimates of the transmissivity from the fluid-injection tests in wells MO Ff 27, MO Ff 29, MO Ff 30 and MO Ff 31 are shown in figure 23. The length of the test intervals in each borehole is denoted by the vertical thickness of the estimate of the transmissivity. The location of the test intervals in each borehole was based on borehole conditions, including the roughness of the borehole wall as interpreted from the caliper log, and the presence of fractures, as interpreted from the acoustic televiewer log. An estimate of the transmissivity of the fractures immediately below the bottom of the surface casing in well MO Ff 27 could not be made because the water level in the borehole was slightly below the bottom of the casing at the time that the testing was conducted in December 2001.

The transmissivity of the tested intervals in the bedrock boreholes varies over five orders of magnitude, from a maximum of approximately 10 ft^2/day to the detection limit of the *in situ* testing apparatus, which is approximately 10^{-4} ft^2/day. In general, the transmissivity of the tested intervals shows an increase in transmissivity with depth in the bedrock boreholes. Fractures immediately below the surface casing in the bedrock at wells MO Ff 30 and MO Ff 31 are likely filled with byproducts of weathering rock. This may have the effect of reducing transmissivity in this zone as indicated from the tests. In contrast, fractures in the unweathered rock at depth are likely to be unfilled and have a higher transmissivity.

Zones of intense fracturing in the bedrock are not necessarily correlated with high transmissivity (figs. 14–17, 23). The density of fracturing, as interpreted from the acoustic televiewer logs, appears to decrease with depth in the boreholes, whereas the transmissivity appears to increase with depth. Transmissivity, however, appears to correlate with the resistivity log; low resistivity correlates with low transmissivity. Low resistivity is usually an indicator of high clay content (Keys and MacCary, 1981), which could be an indication of fracture-fill material due to rock weathering.

The single-hole hydraulic tests do not provide sufficient information to hypothesize on the spatial continuity between boreholes of the intervals of high or low transmissivity. Additional hydraulic tests, which isolate selected intervals of adjacent boreholes and monitor the fluid pressure response in these isolated intervals due to a known hydraulic perturbation, would be needed to identify the spatial continuity of the intervals of high and low transmissivity (Hsieh and Shapiro, 1996).

Multiple-Hole Hydraulic Test A multiple-hole hydraulic test was conducted in the fractured bedrock in the vicinity of the Medical Center Station and Crossover by pumping from well MO Ff 30, while monitoring the change in the water level in the pumped borehole, the bedrock wells (MO Eg 27, MO Ff 27, MO Ff 29, and MO Ff 31), and the piezometer in the saprolite well MO Ff 28. The pump was placed in the bottom of well MO Ff 30, and the pump discharge rate was measured using a totalizing flow meter. Water-level measurements in the bedrock wells and saprolite piezometer were made using pressure transducers with digital records stored in data loggers; check measurements using electric water-level sounders also were made periodically. The multiple-hole test was started on December 10, 2001, at 2:00 p.m.; pumping continued for 3 days, ending on December 13, 2001, at 2:00 p.m. Following the termination of pumping, water levels were recorded for an additional 5 days to monitor the water-level recovery.

The multiple-hole hydraulic test was conducted by pumping at an average rate of approximately 1 gal/min. Based on estimates of the transmissivity from the single-hole tests, a pumping rate less than 1 gal/min was originally selected for this multiple-hole test to maintain the water level above the bottom of the surface casing in the pumped well (MO Ff 30). This was done to avoid dewatering fractures in the bedrock during the hydraulic test, which could result in a reduction of the transmissivity and lead to erroneous estimates of the bulk transmissivity of the fractured bedrock. The pumping rate during the hydraulic test, however, had to be maintained at 1 gal/min or higher because the pump could

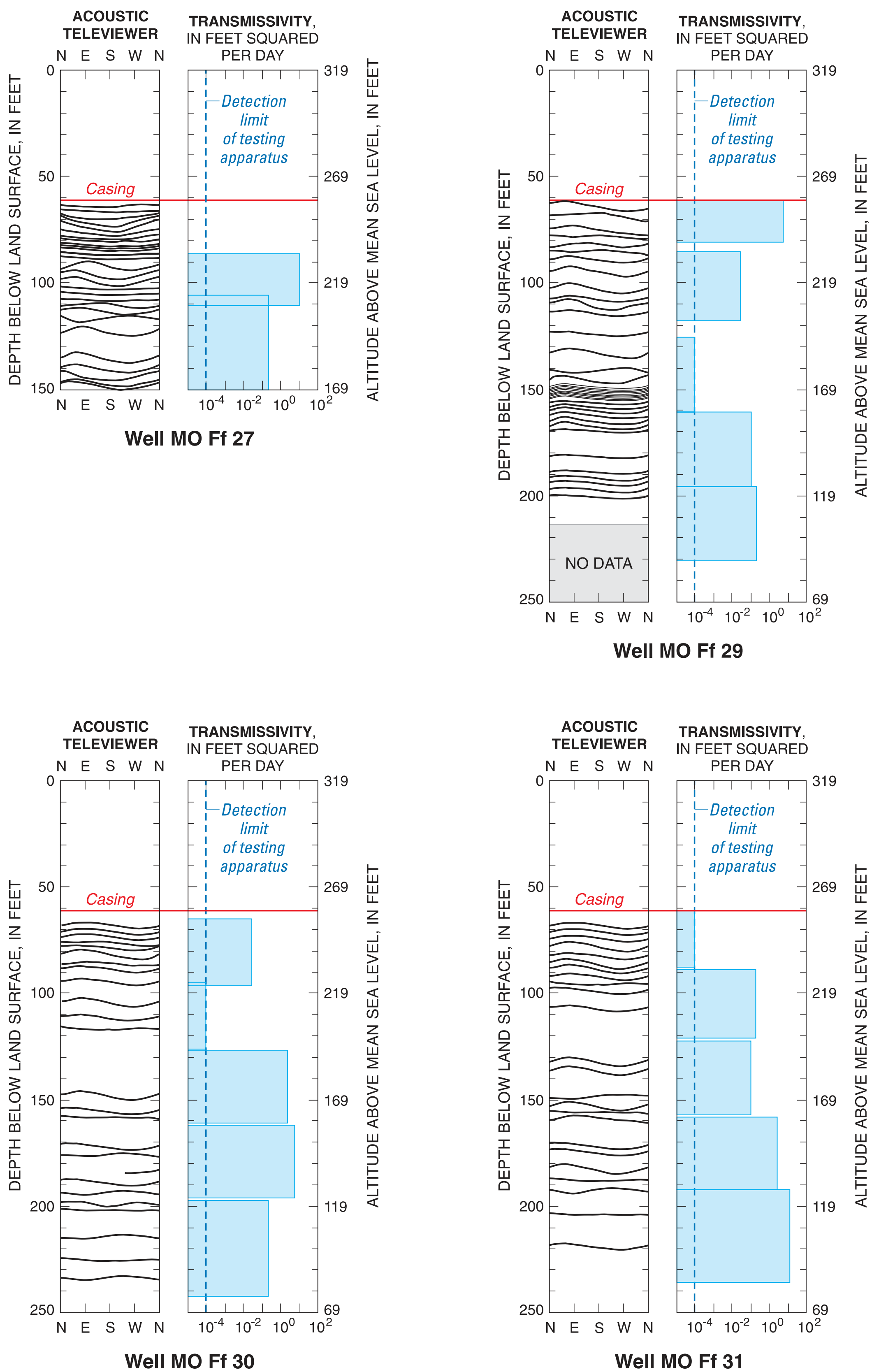


Figure 23. Transmissivity determined from fluid-injection tests in National Naval Medical Center (NNMC) wells MO Ff 27, MO Ff 29, MO Ff 30, and MO Ff 31.

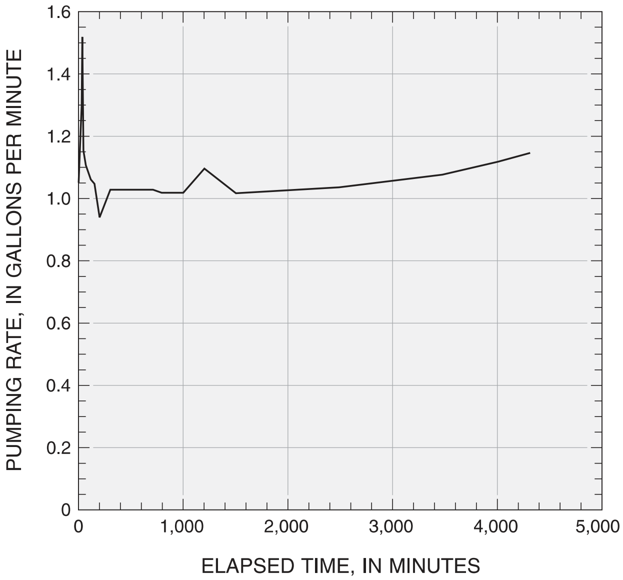


Figure 24. Pumping rate measured at well MO Ff 30 during the hydraulic test started on December 10, 2001, conducted at the National Naval Medical Center (NNMC) well site.

not be operated at a rate lower than 1 gal/min for an extended period of time. After approximately 2 hours of pumping at approximately 1 gal/min, the water level in well MO Ff 30 was lowered below the bottom of the surface casing. When the data were interpreted, however, it appeared that the dewatering of these fractures in the weathered rock immediately below the surface casing in well MO Ff 30 did not affect the overall transmissivity estimate of the rock. Based on the single-hole hydraulic tests, the fractures immediately below the surface casing have a much lower transmissivity than the unweathered rock.

The pumping rate in well MO Ff 30 during the hydraulic test is shown in figure 24. The drawdown in saprolite well MO Ff 28 and bedrock wells MO Ff 29, MO Ff 30, and MO Ff 31 during the hydraulic test is shown in figure 25. The drawdown measured in these wells is the difference between the time-varying depth to water in the well during pumping and the depth to water at the onset of pumping (Bear, 1979). MO Ff 29 and MO Ff 31 were the only bedrock wells other than the pumped well to show a hydraulic response to pumping. The observation well finished in the saprolite showed only a small response (less than 0.1 ft change in water level) to the 3 days of pumping in well MO Ff 30.

The measured drawdown in MO Ff 29, MO Ff 30, and MO Ff 31 is plotted against the logarithm of time on figure 25. After approximately 1.5 days (approximately 2,160 minutes), there is a sharp increase in the drawdown measured in each well, which is an artifact of the increased pumping rate toward the end of the multiple-hole hydraulic test. Furthermore, the drawdown measured in the pumped well and two observation wells does not show appreciable leakage from the saprolite to the fractured bedrock, indicating that the saprolite has a limited vertical hydraulic connection to the bedrock.

The formation transmissivity of the bedrock can be estimated from the straight-line portion (slope) of the plot of the drawdown against the logarithm of time in figure 25 (Fetter, 2001; Lohman, 1979). The transmissivities estimated from the drawdown recorded in the pumped well (MO Ff 30) and the two observation wells (MO Ff 29 and MO Ff 31) are all equal to 3.7 ft^2/day. This estimate of transmissivity is approximately one-half an order of magnitude less than the maximum transmissivity estimated from single-hole hydraulic tests conducted in MO Ff 30, and approximately one-half an order of magnitude less than the maximum transmissivity estimated from the single-hole hydraulic tests conducted in all other bedrock wells. The multiple-hole hydraulic test was conducted without borehole packers to isolate discrete intervals in any of the bedrock wells, whereas the single-hole hydraulic tests were conducted on short hydraulically isolated intervals in the wells. Because transmissivity estimated from the multiple-hole hydraulic test is one-half an order of magnitude less than the estimate from the single-hole hydraulic tests, this implies that the intervals of high transmissivity detected by the single-hole hydraulic tests are not areally extensive. The intervals of high transmissivity detected in each borehole are likely connected by fractures with slightly lower transmissivity, resulting in a bulk transmissivity of the fractured bedrock that is less than the maximum transmissivity estimated from the single-hole hydraulic tests.

The formation storativity of the bedrock aquifer can also be estimated from the straight-line portion of the plot of the drawdown against the logarithm of time for the two observation wells, MO Ff 29 and MO Ff 31 (Lohman, 1979). The formation storativity is the volume of water released from compressive storage over the thickness of the bedrock aquifer per unit decline in the hydraulic head (Bear, 1979). The storativity associated with the drawdown measured in boreholes MO Ff 29 and MO Ff 31 is 1.8×10^{-4} and 1.0×10^{-5}, respectively. The conceptual model used to estimate the storativity is based on the assumption of an aquifer with homogeneous hydraulic properties. The difference in the storativity between these two observation wells is likely the result of aquifer heterogeneity. A further indication of heterogeneity in aquifer properties is the fact that plots of drawdown against time divided by radius squared (t/r_w^2) for wells MO Ff 29, MO FF 30, and MO Ff 31 do not overlay each other (fig. 26), where “ t ” is the elapsed time since the start of pumping and r_w^2 is the square of the radial distance from the pumped well to the observation borehole (Lohman, 1979). Additional hydraulic tests, which isolate selected intervals of adjacent boreholes and monitor the fluid pressure response in these isolated intervals due to a known hydraulic perturbation, would be needed to identify the aquifer heterogeneity (Hsieh and Shapiro, 1996).

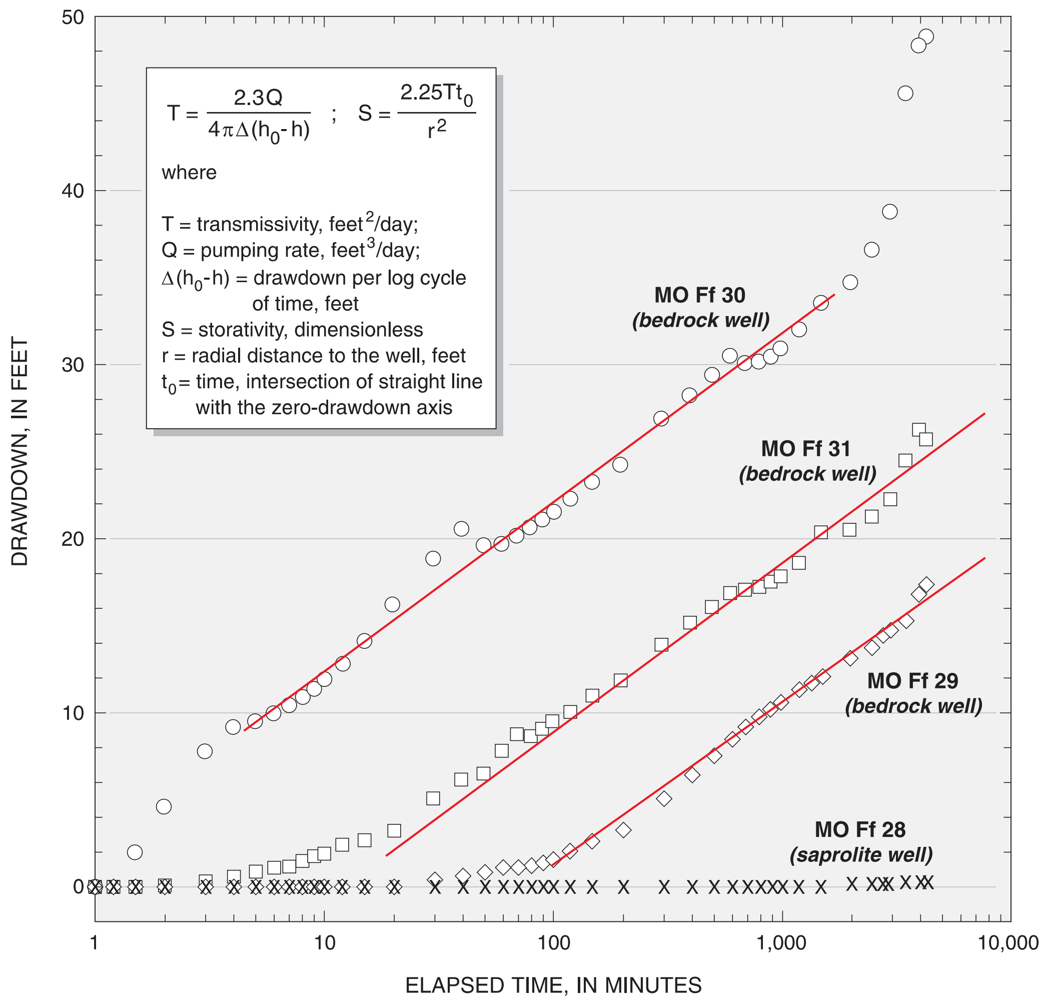


Figure 25. Measured drawdown in saprolite well MO Ff 28 and bedrock observation wells MO Ff 29, MO Ff 30, and MO Ff 31 during the hydraulic test started on December 10, 2001, conducted at the National Naval Medical Center (NNMC) well site.

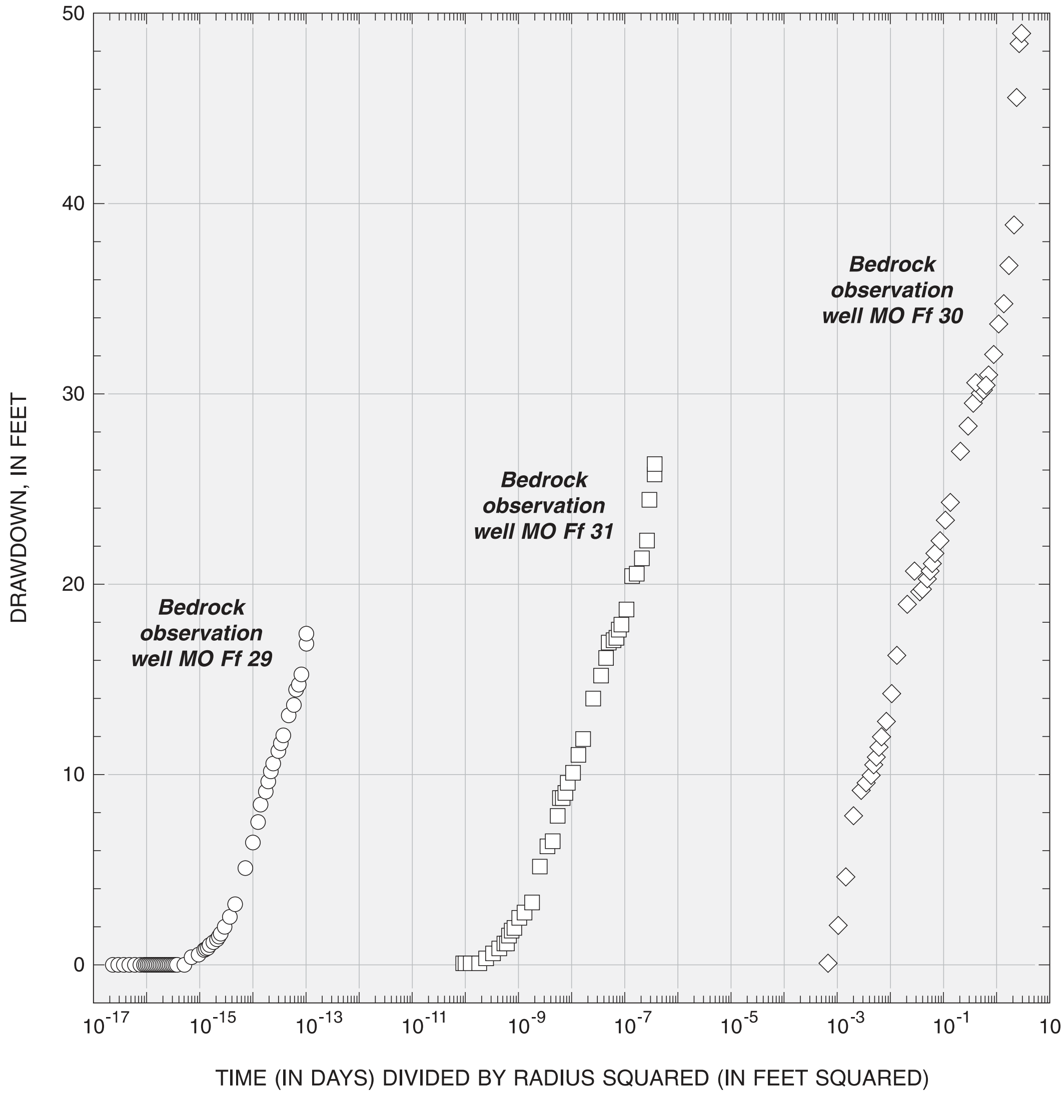


Figure 26. Time divided by radius squared plot for the hydraulic test started on December 10, 2001, conducted at the National Naval Medical Center (NNMC) well site.

Hydrogeologic Controls on Ground-Water Discharge to the Subway Tunnel Near the Medical Center Station and Crossover

The major hydrogeologic controls on ground-water flow into the Medical Center Station and Crossover include geologic factors, hydraulic heads and gradients, leakage from saprolite to bedrock, and permeability of the fractures in the bedrock. In the vicinity of the Medical Center Station and Crossover, the two major geologic units are the Sykesville Formation (€s) and the biotite-hornblende tonalite (Ogh) member of the Georgetown Intrusive Suite (Fleming and others, 1994; Drake, 1998). The mapped structural planar features (foliation and joints) of the areally extensive Sykesville Formation (€s) are oriented in a predominantly north-south direction, which is aligned with the tunnel (fig. 7). The Medical Center Station and Crossover are in the biotite-hornblende tonalite member of the Georgetown Intrusive Suite where the mapped foliation and joints are predominantly in an east-west direction (perpendicular to the tunnel). If it is inferred that these orientations (strike) are the preferred direction of ground-water flow, then there may be greater inflow of ground water to the tunnel when the fractures are in an east-west orientation, which is perpendicular to the tunnel. Analysis of fracture orientations with depth (up to 240 ft below land surface) in test wells drilled near the Medical Center Station and Crossover shows that the strike of the fractures is also in this east-west orientation, which is consistent with the regionally mapped orientations of the foliation and joints. This fracture orientation of the biotite-hornblende tonalite may increase the potential for ground-water flow into the tunnel. Ground-water flow directions based on regional hydraulic heads in the bedrock (Sykesville Formation and biotite-hornblende tonalite) show an abrupt change in direction at the contact between the Sykesville Formation and biotite-hornblende tonalite.

Based on data from five observation wells, hydraulic heads in the bedrock near the Medical Center Station and Crossover are responsive to precipitation. The monitoring well in the saprolite near this area shows little response to precipitation; the data from this well indicate that water levels in the saprolite are fairly constant with time.

In general, the hydraulic head in the bedrock decreases with depth in the test wells at the NNMC site, and the hydraulic head is higher in the saprolite than in the bedrock, indicating the potential for downward flow. This potential for downward ground-water flow implies that water in the saprolite is recharging the bedrock aquifer. The significance of this connection is unknown at this time; however, pumping in the bedrock for 3 days at the NNMC site resulted in a negligible hydraulic response in the saprolite. This implies that there is a low vertical hydraulic conductivity between the saprolite and the unweathered bedrock. The fractures at the top of the competent bedrock in wells at the NNMC site have transmissivities below the detection limit of the *in situ* testing equipment (less than 10^{-4} ft^2/day). The fractures are likely filled with weathering products, reducing their ability to transmit ground water. In contrast, the transmissivity of the fractures at greater depths in the boreholes at the NNMC site were at or near 10 ft^2/day.

The potential or driving force for water intrusion into the Medical Center Station and Crossover is due to the difference between the hydraulic head in the fractures in the surrounding rock and the tunnel, which is at atmospheric pressure. Because the tunnel is at atmospheric pressure, an increase in hydraulic heads in the bedrock results in an increased hydraulic gradient and thus a larger volume of water intruded into the tunnel. The volume of water entering the Medical Center Station and Crossover was measured by instrumenting the A6 pumping station with a flow meter that measures hourly discharge. This station collects water from a large section of tunnel from just north of the Bethesda Station to the portal north of the Medical Center Station (fig. 1b).

The discharge hydrograph of daily pumping at A6 (fig. 27) is correlated with heads measured near the tunnel in bedrock observation well MO Eg 27 (table 2, fig. 27). More water is pumped from the tunnel when the hydraulic heads in the bedrock increase. The tunnel pressure remains at atmospheric pressure; thus, a higher hydraulic head in the bedrock implies a larger hydraulic gradient and a larger driving force for ground-water flow into the tunnel.

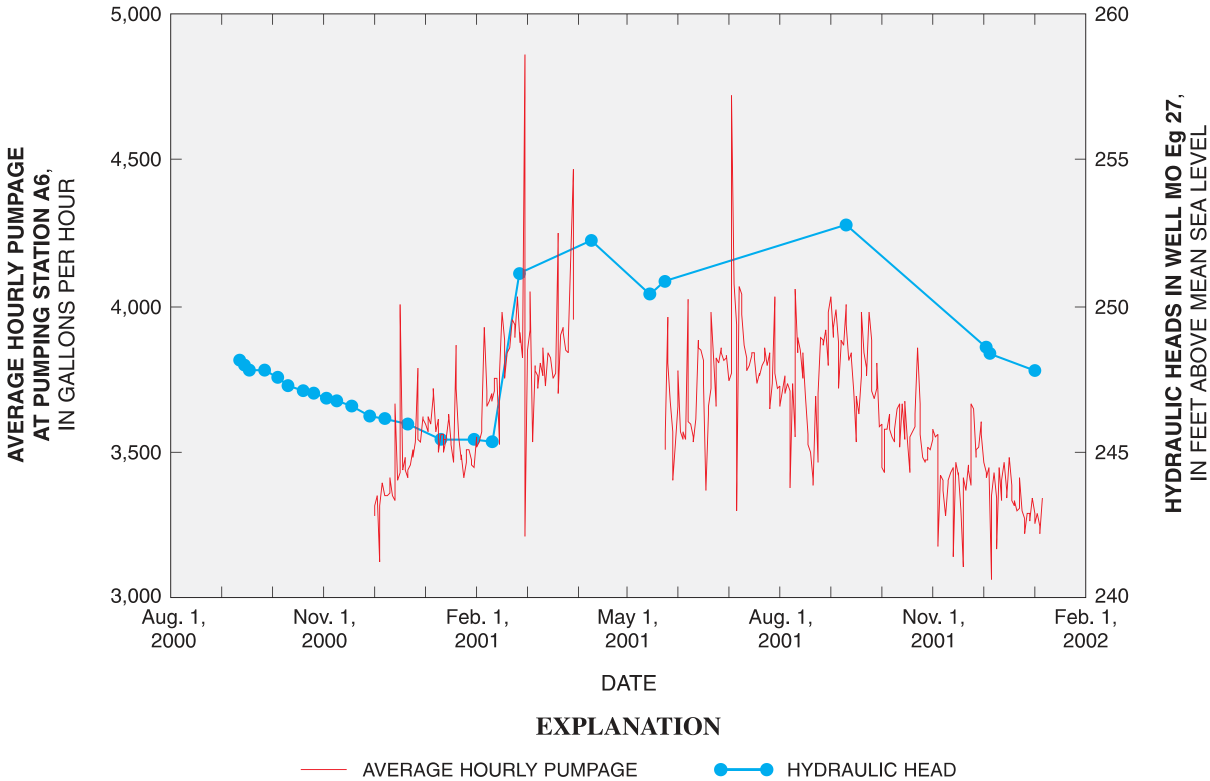


Figure 27. Comparison of hydraulic heads in observation well MO Eg 27 and hourly pumpage at pumping station A6. *(Refer to figure 1b.)*

Summary and Conclusions

Excessive water intrusion has been observed inside several of the Washington Metropolitan Area Transit Authority subway tunnels, with the worst leakage occurring along the Red Line. The Red Line tunnels and stations from Dupont Circle north were constructed in bedrock that contains permeable (water-bearing) joints and fractures. Excessive water leakage through the walls and the presence of water inside the underground facilities has damaged mechanical and electrical components in the tunnel, and has escalated the deterioration rate of the rail system. This leakage will eventually reduce the life span of the structure and rail system. Current water mitigation practices include the application of sealant to cracks that are leaking or diverting flow from the ceiling to the drain system with small “aluminum tents.” In order for the engineers and managers of the Washington Metropolitan Area Transit Authority to develop a strategy to prevent or reduce water intrusion inside the underground facilities, an understanding of the hydrogeologic controls on water intrusion was needed. To meet this need, the U.S. Geological Survey and the Washington Metropolitan Area Transit Authority conducted a cooperative hydrogeologic investigation from 2000–03 to characterize groundwater flow into the tunnel system. Results of this study provide a methodology for investigating similar water intrusion problems in subway tunnels constructed in fractured bedrock, and may provide helpful information in the design of methods to divert or reduce the volume of water entering subway tunnels.

The Red Line near the Medical Center Station and Crossover passes through or beneath two fractured bedrock lithologic units, the Sykesville Formation and the biotite-hornblende tonalite member of the Georgetown Intrusive Suite. Overlying the unweathered bedrock is a transition zone of varying thickness that consists of decomposed rock. Overlying the transition zone is saprolite, a residual deposit of soft, red/brown to gray, earthy, weathered porous material formed from decomposed crystalline rock in which constituent minerals, other than quartz, have been altered to clays. Seismic refraction and 2-D resistivity profiles indicate that the saprolite thickness ranges from 20 to 55 feet, and identified several possible anomalies in the saprolite-bedrock contact that may indicate intensive fracturing. Slug tests conducted in the saprolite near the Medical Center Station and Crossover estimated a transmissivity (T) of 10 feet squared per day, hydraulic conductivity (K) of 1 foot per day, and storativity (S) of 10^{-6}.

The mapped foliation and joints of the Sykesville Formation in the vicinity of the Medical Center Station and Crossover are generally oriented north-south, with a mean orientation of about 358 degrees and a standard error of plus or minus 10 degrees. In the biotite-hornblende tonalite, the general orientation of the structural features is shifted 90 degrees to an east-west direction, with a mean orientation of 88 degrees and a standard error of plus or minus 34 degrees. The orientation of the foliation and joints may influence the direction and rate of ground-water flow.

Fracture analysis in the four bedrock boreholes at the National Naval Medical Center well site shows the fractures are in an east-west orientation, which matches the orientation of the mapped foliation and joints in the biotite-hornblende tonalite. The mean dip of the fractures at the National Naval Medical Center well site is about 65 degrees; thus, the majority of fractures are steeply dipping. The abrupt directional change in ground-water-flow directions based on mapped hydraulic heads at the contact between the Sykesville Formation and biotite-hornblende tonalite coincides with a change in fracture orientation in these two geologic units. The east-west fracture orientation of the biotite-hornblende tonalite may have an influence on ground-water flow and could explain some of the increased water intrusion at the Medical Center Station.

Monthly precipitation records at nearby National Oceanic and Atmospheric Administration Precipitation Station 2325 (Dalecarlia Reservoir in Washington, D.C.) and the hydrographs from the bedrock wells and the one saprolite observation well were correlated to investigate ground-water recharge in the vicinity of the Medical Center Station and Crossover. Although the single well in the saprolite showed little response to precipitation events, the heads in the bedrock wells were quite responsive to monthly precipitation.

The transmissivity of the tested intervals in the bedrock boreholes varies over five orders of magnitude, from a maximum of approximately 10 feet squared per day to the detection limit of the *in situ* testing apparatus, which is approximately 10^{-4} feet squared per day. In general, the transmissivity of the tested intervals shows an increase with depth. The low transmissivity immediately below the surface casing in the bedrock is likely due to a gradation in rock weathering. Fractures in close proximity to the saprolite are likely to be filled with byproducts of rock weathering, resulting in reduced transmissivity; in contrast, fractures in the unweathered rock at depth are probably unfilled.

In general, hydraulic head decreases with depth in the bedrock boreholes, indicating the potential for downward ground-water flow. The head difference between the saprolite and bedrock also indicates a potential for downward ground-water flow, and implies that the water in the saprolite is recharging the bedrock aquifer.

Transmissivities estimated from the drawdown recorded in the pumped well and the two observation wells are equal to 3.7 feet squared per day. This estimate is approximately one-half an order of magnitude less than the maximum transmissivity estimated from the single-hole hydraulic tests conducted in well MO Ff 30, and approximately one-half an order of magnitude less than the maximum transmissivity estimated from the single-hole hydraulic tests conducted in all other bedrock wells. The multiple-hole hydraulic test was conducted without borehole packers to isolate discrete intervals in any of the bedrock wells, whereas the single-hole hydraulic tests were conducted on short, hydraulically isolated intervals in the boreholes. Because transmissivity estimated from the multiple-hole test is one half an order of magnitude less than the transmissivity estimated from the single hole tests, this implies that the intervals of high transmissivity detected by the single-hole hydraulic tests are not areally extensive. The intervals of high transmissivity detected in each borehole are likely connected by fractures with slightly lower transmissivity, resulting in a bulk transmissivity of the fractured bedrock that is less than the maximum transmissivity estimated from the single-hole tests.

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