

Delineation of Ground Water Flow in Fractured Rock in the Southwestern Part of Manhattan, New York, Through Use of Advanced Borehole Geophysical Methods

by Frederick Stumm and Shafiul Chowdhury

Abstract

Advanced borehole-geophysical methods were used to assess the geohydrology of fractured crystalline bedrock at five test boreholes in southwestern Manhattan Island, New York, in preparation for construction of a third water tunnel for New York City. The boreholes penetrated gneiss and other crystalline bedrock that has an overall southwest to northwest dipping foliation with a 60° dip. Most of the fractures encountered are either nearly horizontal or have moderate northwest dip azimuths. Fracture indexes range from 0.25 to 0.44 fracture per foot (0.3 m) of borehole.

Electromagnetic (EM) and heat-pulse flowmeter logs obtained under ambient and pumping conditions, together with other geophysical logs, indicate transmissive fracture zones in each borehole. Pumping tests of each borehole indicated transmissivity ranges from <2 to 360 ft²/day (0.2 to 33 m²/day). Ground water appears to flow within an interconnected fracture network toward the south and west within the study area. No correlation was indicated between the fracture index and the total borehole transmissivity.

Introduction

Manhattan Island is ~12.5 miles (20.1 km) long and 2 miles (3.22 km) wide (Figure 1) and consists of high-grade metamorphic bedrock that outcrops in some areas. Unconsolidated deposits overlying the metamorphic bedrock range from zero to more than 200 feet (61 m) thick. Manhattan Island is bounded by saltwater—on the west by the Hudson River, on the east by the East River, and on the south by New York Harbor.

The U.S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection (NYCDEP), began a research project to apply advanced borehole-geophysics to assess the geohydrology of the crystalline bedrock in southeastern New York. These techniques were applied to five boreholes along the western part of Manhattan Island to identify (1) the bedrock lithology, (2) the location and orientation (true strike and dip) of fractures and foliation of the bedrock intersected by the boreholes, (3) the hydraulic characteristics of transmissive fracture zones, and (4) major fractures or faults that lie as much as 100 feet (30.5 m) beyond each of the boreholes (using borehole radar).

This paper (1) outlines the geophysical methods used; (2) describes the geology of the study area; (3) presents geophysical logs and summarizes the geophysical interpretations of fractures, faults, and foliation intersected by each bore-

hole; (4) presents ground water levels, fluid-temperature and resistivity logs, and pumping and drawdown data; and (5) summarizes the transmissivity and locations of transmissive fractures in the boreholes.

Methodology

Borehole-Geophysical Logging

Borehole-geophysical logs collected for this study included natural gamma, single-point-resistance (SPR), mechanical and acoustic caliper, focused electromagnetic induction (EM), magnetic susceptibility (MAG), borehole-fluid temperature and resistivity, heat-pulse and EM flowmeter, borehole deviation, acoustic and optical televiewer (ATV and OTV), and borehole radar. The logging methods have been described by Keys (1990), Serra (1984), Keys and MacCary (1971), McNeill et al. (1996), Paillet (1998), Williams and Lane (1998), Singha et al. (2000), and Stumm et al. (2000, 2001a, and 2001b).

Borehole Network

Five NX-sized (3-inch [7.6 cm] diameter) boreholes (W55ST-A, W37ST-A, W34ST-B, W26ST-A, and Grove ST-A) were drilled and cased through the unconsolidated

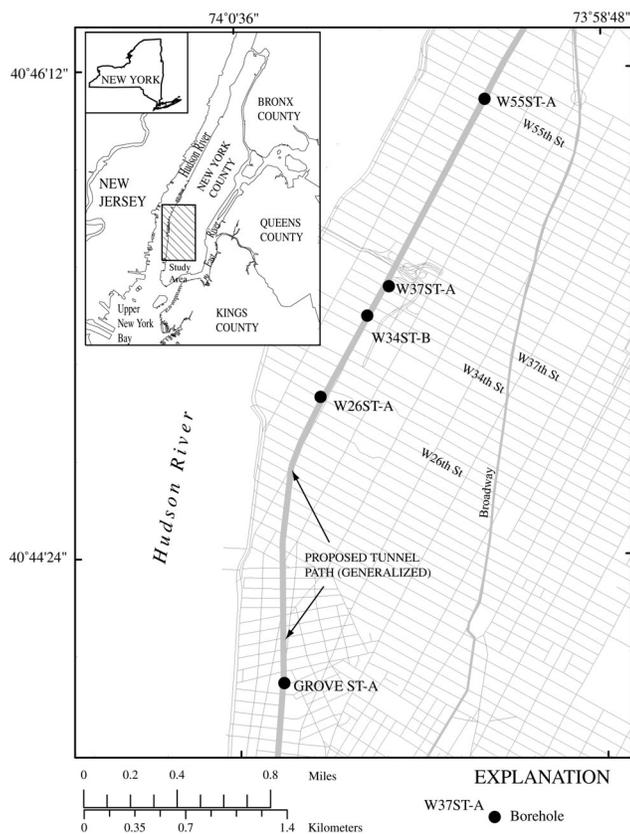


Figure 1. Location of study area boreholes in the southwestern part of Manhattan Island, New York.

deposits to the top of bedrock, and were open from the bedrock surface to the bottom of the drilled depth (Figure 1 and Table 1).

Geohydrology

Manhattan Island is underlain by high-grade metamorphic bedrock consisting of a sequence of gneiss, schistose-gneiss, and marble (Merrill 1890; Hobbs 1905; Berkey 1910; Murphy and Fluhr 1944; Baskerville 1994). The bedrock contains many faults and fractures, some of which are transmissive (can transmit water). Depth to bedrock in the five boreholes ranges from 8 to 80 feet (2.4 to 24.4 m) below land surface (bls). Perlmutter and Arnow (1953) described the unconsolidated sediments in southern Manhattan as consisting of Pleistocene aged sand, gravels, and silty clays.

The ATV, OTV, and borehole-radar data indicate that all five boreholes penetrate moderately fractured rock that contains highly fractured zones and transmissive fractures.

Structural trends of these geologic units and the borehole radar data from three of the boreholes indicate that most of the large-sized fractures and faults detected in each borehole extend some distance beyond the borehole (Stumm et al. 2001b).

Geologic-Structure Analysis

Foliation and fractures encountered in each borehole were delineated from the OTV and ATV data. Fractures were classified as small apertures of 0.04 inch (1 mm) or less, medium apertures of >0.04 to 0.39 inch (>1 to 10 mm), large apertures >0.39 to 9.8 inches (>10 to 25 cm), or very large apertures >9.8 inches (>25 cm), depending on the apparent aperture or width of the opening (Stumm et al. 2001b). Measured fracture apertures in the boreholes are considered apparent to account for possible alterations caused by the drilling process.

Orientations of fractures intersected by each borehole were calculated using data from the ATV and OTV logs. The orientations were then converted through standard equal-area net projections as poles to planes.

Structure orientations for fractures or foliation are displayed as “tadpoles,” which are circles with “tails” plotted with respect to depth, and to a horizontal scale to indicate the degree of dip-plunge angle of the structures from 0° to 90°. The tail of each tadpole points to the dip azimuth of the structure.

Analysis of the fractures intersected by each borehole included the fracture index. The total number of fractures detected in each borehole was divided by the thickness of bedrock encountered to provide a fracture index indicating the average number of fractures per foot (0.3 m) of bedrock.

Fractures and Faults

Fracture analysis of equal-area nets identify populations or clusters with similar dip azimuths and dip angles. No general correlation between fracture orientation and depth is evident. Overall total borehole fracture-population orientations are (1) nearly horizontal, and (2) moderate angle dip with a west to northwest dip azimuth. Many fractures were detected within the five boreholes with dip angles in excess of 70°. Five small faults that intersect the boreholes were delineated using the OTV.

Foliation

Foliation analyses of equal-area nets and tadpole plots, grouped by depth, indicate populations or clusters with similar dip azimuths and dip angles. Total borehole foliation (mean

Table 1
Borehole Dimensions and Hydraulic Properties

Borehole	USGS Well Number	Length of Borehole (ft)	Length of Steel Casing (ft)	Fracture Index (fractures/ft)	Specific Capacity ([gal/min]/ft)	Total Borehole Transmissivity (ft ² /day)	Water-Level Elevation (ft)
W55ST-A	NY-170	619.4	150	0.25	0.05	11	29.1
W37ST-A	NY-191	651.4	15	0.40	1.22	360	13.5
W34ST-B	NY-168	625.7	8	0.44	0.27	75	10.5
W26ST-A	NY-176	567.3	30	0.37	0.13	35	4.8
GroveST-A	NY-199	644.0	77	0.44	0.01	2	0.4

orientation) at the test boreholes ranged from southwesterly to northwesterly with a mean dip plunge angle of 60°.

Ground Water Flow Analysis

Ground water levels (hydraulic head) were measured at five boreholes during field visits from November 1998 to 2002. Fluid-temperature, fluid-resistivity, and flowmeter logs were collected at each borehole (except W55ST-A and only partially at W26ST-A) during ambient and pumping conditions. Fluid-temperature and resistivity logs were used to help delineate transmissive fractures within the boreholes. Changes in fluid temperature and resistivity may occur at transmissive fractures. The drawdown, pumping rate, and total pumping time at each borehole during test pumping were analyzed by a computer program (Bradbury and Rothschild 1985) to calculate specific capacity and transmissivity of the entire open borehole (Table 1).

Transmissivity

Calculated transmissivity values for the boreholes range from <2 to 360 ft²/day (0.2 to 33 m²/day) (Table 1). The transmissive fracture network seems to be a discrete system not correlated specifically with the fracture index (Table 1). Several fractures were highly transmissive; however, the majority of fractures detected were not transmissive.

The flowmeter logs were analyzed through techniques of Paillet (1998, 2000, 2001), whereby differences between flow values at adjacent fracture zones within each borehole are attributed to measurement scatter and a possible net difference in borehole flow. Therefore, flow-log interpretation involves identification of the relative amounts of inflow or outflow occurring at specific depth intervals (fracture zones). Analyzing flow under ambient and pumping conditions can eliminate the effects of hydraulic-head differences between zones, in accordance with the techniques of Molz et al. (1989) and Paillet (2000).

Ground Water Levels in Fall 1999 and Summer 2000

Water levels in the fractured bedrock range from 0.4 to 29.1 feet (0.12 to 8.87 m) above sea level. Preliminary distribution of hydraulic heads seems to indicate a continuum of interconnected fractures with an area of ground water recharge in the central part of the island and discharge areas along the coastline. The hydraulic head in fractured bedrock wells represents the transmissivity-weighted average of the hydraulic heads of all transmissive fractures in the borehole.

Delineation of Faults, Fractures, Foliation, and Ground Water Flow

Faults, fractures, and foliation were interpreted from OTV, ATV, borehole-radar, gamma, SPR, EM, MAG, and caliper logs. The hydraulic characteristics of the bedrock fractures at each borehole were determined from the fluid-temperature, fluid-resistivity, and flowmeter logs. OTV data (fracture depth, fracture orientation, and foliation orientation) were used to delineate all fractures, faults, and foliation in the boreholes. At least five small faults were detected by OTV logs in the boreholes, but were analyzed as fractures.

Borehole W55ST-A

A partial collapse of the W55ST-A borehole within bedrock required the installation of steel casing to 150 feet (45.7 m) below land surface (bls) to facilitate geophysical logging (Figure 1). As a result, fracture, foliation, and ground water data were not collected from the top of bedrock at 34 feet (10.4 m) bls to the bottom of the inserted casing at 150 feet (45.7 m) bls (Figure 2a). This borehole thus is considered undersampled.

Fractures and Foliation

The ATV and OTV data indicate 126 fractures from the bottom of the inserted casing to the bottom of the borehole (Figure 2a) with a fracture index of 0.25 fracture per foot (0.3 m) of borehole. The mean orientation for the 126 fractures is N19°E 44°NW. Two fracture-population clusters are indicated: one is nearly horizontal, dipping slightly to the east (minority cluster); the second dips northwestward (majority cluster). The mean orientation of foliation for the entire borehole is N16°E 60°NW.

The gamma-log analysis indicates uniform gamma counts throughout most of the borehole, except at isolated locations that relate to lithology and/or fractures (Figure 2a). The SPR log has conductive spikes, some that correspond to fractures at 226 to 231 and 475 feet (68.9 to 70.5 and 145 m) bls. The bedrock seems to increase in resistance with depth. The MAG log shows a zone from 190 to 375 feet (58 to 114 m) bls of magnetite-rich bedrock (Figure 2a).

Ground Water Flow Zones

Hydraulic heads in W55ST-A had a mean elevation of 29.1 feet (8.87 m) and appeared to be tidally affected. The partially collapsed borehole conditions hampered the ability to calculate transmissivity of some individual fracture zones.

Heat-pulse flowmeter and fluid-resistivity logs indicate three transmissive fracture zones at 162 to 170, 226 to 231, and 330 to 619.4 feet (49.3 to 51.8, 68.9 to 70.4, and 100.6 to 188.7 m) bls (Figure 2b). Three medium fractures at the 162 to 170 feet (49.3 to 51.8 m) bls fracture zone indicate no detectable ambient flow but significant upflow and transmissivity during pumping. The fluid-resistivity log indicates a deflection or slope change at the 226 to 231 feet (68.9 to 70.4 m) and 342 to 380 feet (1.4.2 to 115.8 m) bls fracture zones, and the heat-pulse flowmeter indicates no detectable ambient flow and only minor upflow during pumping (Figure 2b). Pumping at a rate of 1.1 gal/min (6 m³/day) for 1.9 hours produced a drawdown of 24.2 feet (7.4 m), or a specific capacity of 0.05 (gal/min)/ft (0.88 m³/day/m). Total borehole transmissivity was calculated to be 11 ft²/day with estimated transmissivities of 5.6, 0.3, and 5.1 ft²/day (0.52, 0.03, 0.47 m²/day) for the three fracture zones, respectively.

Borehole W37ST-A

Fractures and Foliation

The ATV and OTV data indicate a total of 254 fractures from below the casing to the bottom of borehole W37ST-A (Figures 1 and 2c), with a fracture index of 0.40 fracture per foot (0.3 m) of borehole. The mean orientation for the 254

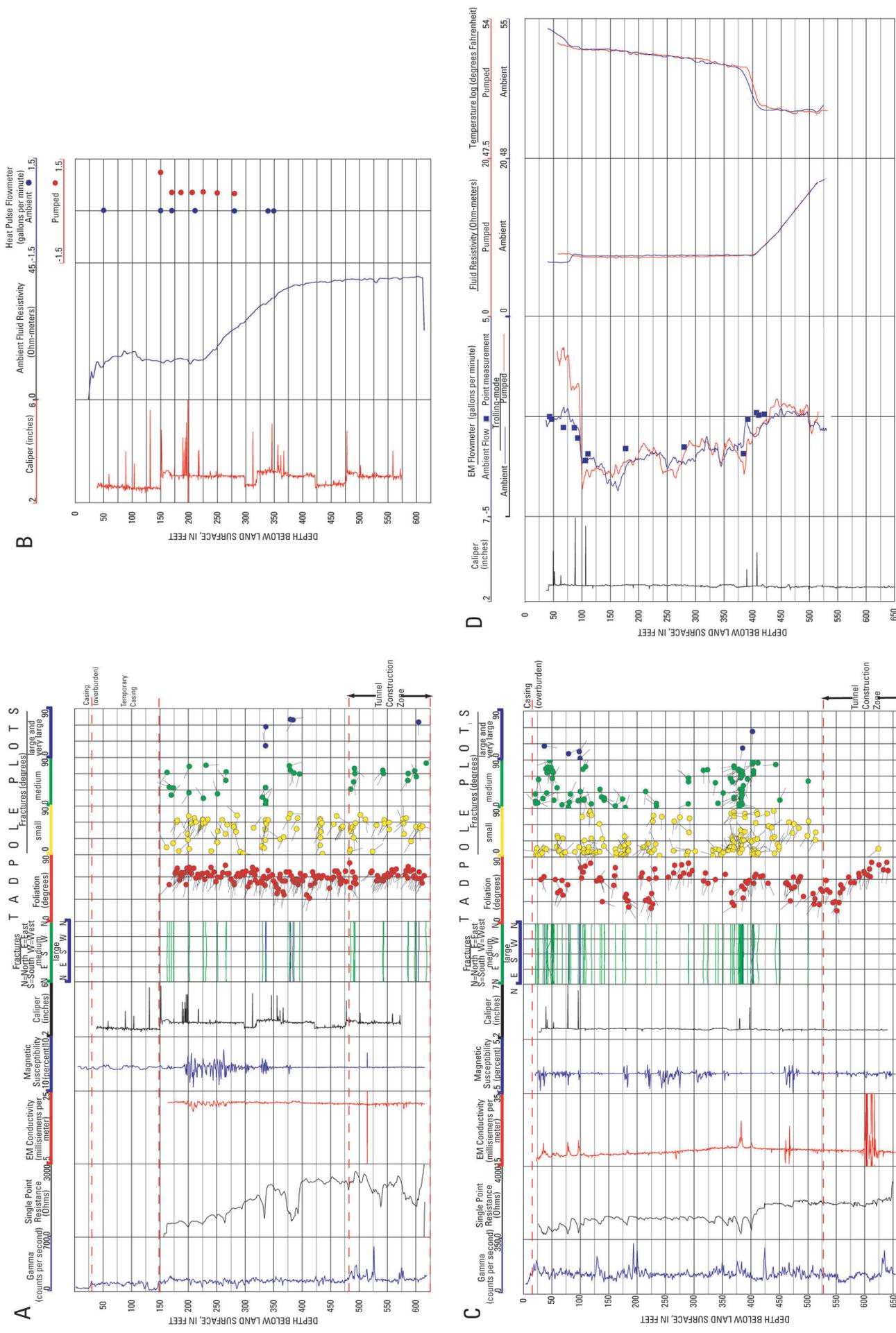


Figure 2. Suite of geophysical logs from boreholes W55ST-A (a and b) and W37ST-A (c and d), Manhattan, New York.

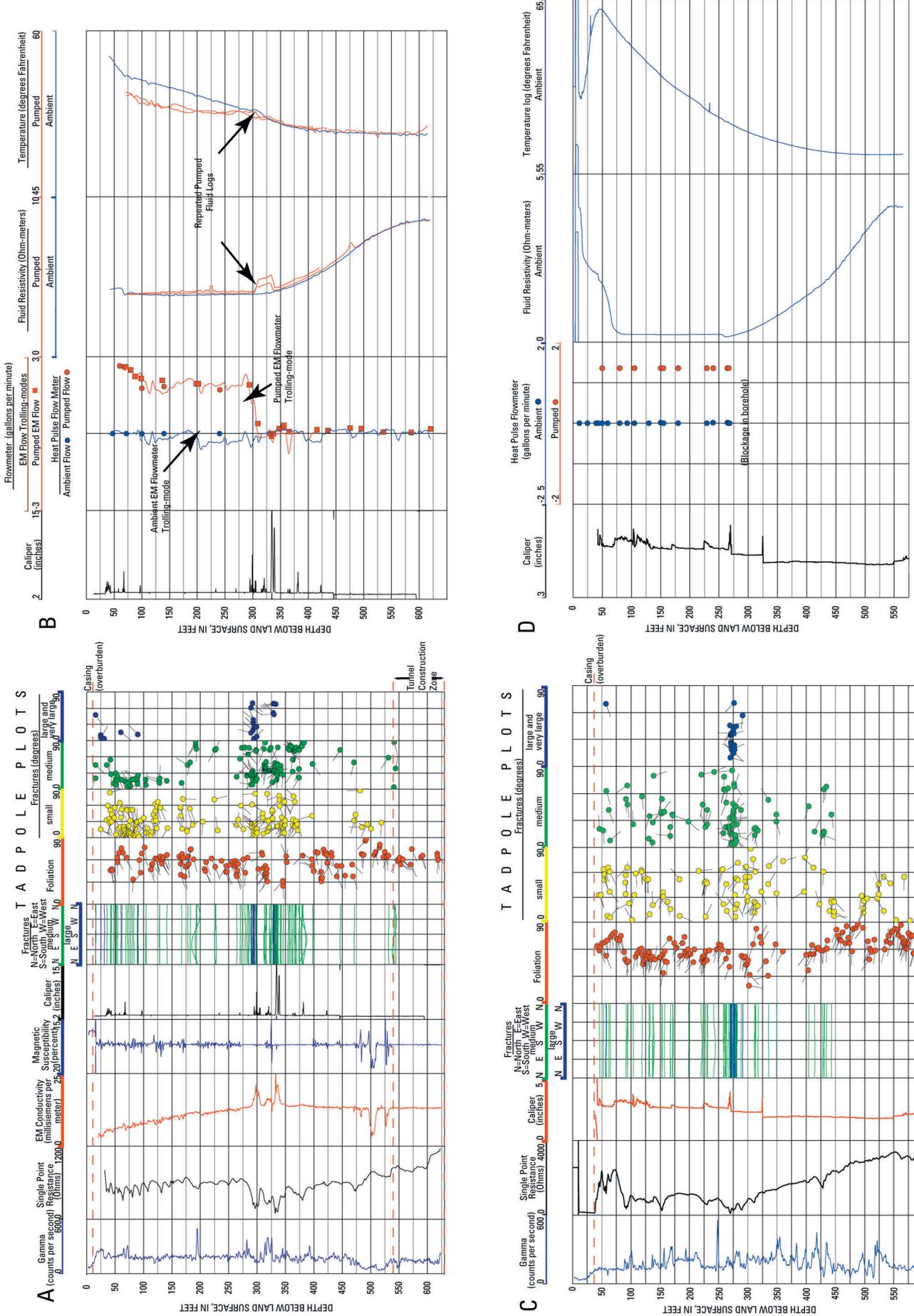


Figure 3. Suite of geophysical logs from boreholes W34ST-B (a and b) and W26ST-A (c and d), Manhattan, New York.

fractures is N25°E 08°NW. Two fracture-population clusters are indicated in the stereonet: one is nearly horizontal (majority cluster); the other has a low angle dip northward (minority cluster). The mean orientation of total foliation is N06°E 55°NW.

The gamma-log analysis indicates uniform gamma counts throughout the borehole except at a few isolated locations that correspond to minor mineralogical changes (Figure 2c). The SPR and EM logs show deflections that indicate weathered alteration minerals at four large fracture zones at 80, 100, 385, and 403 feet (24.4, 30.5, 117.3, and 122.8 m) bls.

Ground Water Flow Zones

Hydraulic heads in W37ST-A had an average elevation of 13.5 feet (4.1 m). The water levels at this borehole did not appear to be tidally affected. At this borehole, the hydraulic

conditions and resolution of the EM flowmeter measurements precluded quantitative estimation of the transmissivity of specific fracture zones.

EM flowmeter, fluid-temperature, and fluid-resistivity logs from W37ST-A indicate several transmissive fracture zones (Figure 2d). EM flowmeter analysis indicated downward flow from the 50 to 60 feet (15.2 to 18.3 m), 98 to 100 feet (29.9 to 30.5 m), and 385 feet (117.3 m) bls zones to the 403 feet (122.8 m) bls zone. The failure of pumping to reverse the direction of flow below the 98 to 100 feet (29.9 to 30.5) bls zone indicates significant transmissivity within the 50 to 60 feet (15.2 to 18.3 m) and 98 to 100 feet (29.9 to 30.5 m), bls fracture zones, and relatively low hydraulic head at the 403 feet (122.8 m) bls zone (Figure 2d).

The borehole was pumped at a rate of 3.0 gal/min (16.4 m³/day) for 1.7 hours and produced a drawdown of 2.46 feet

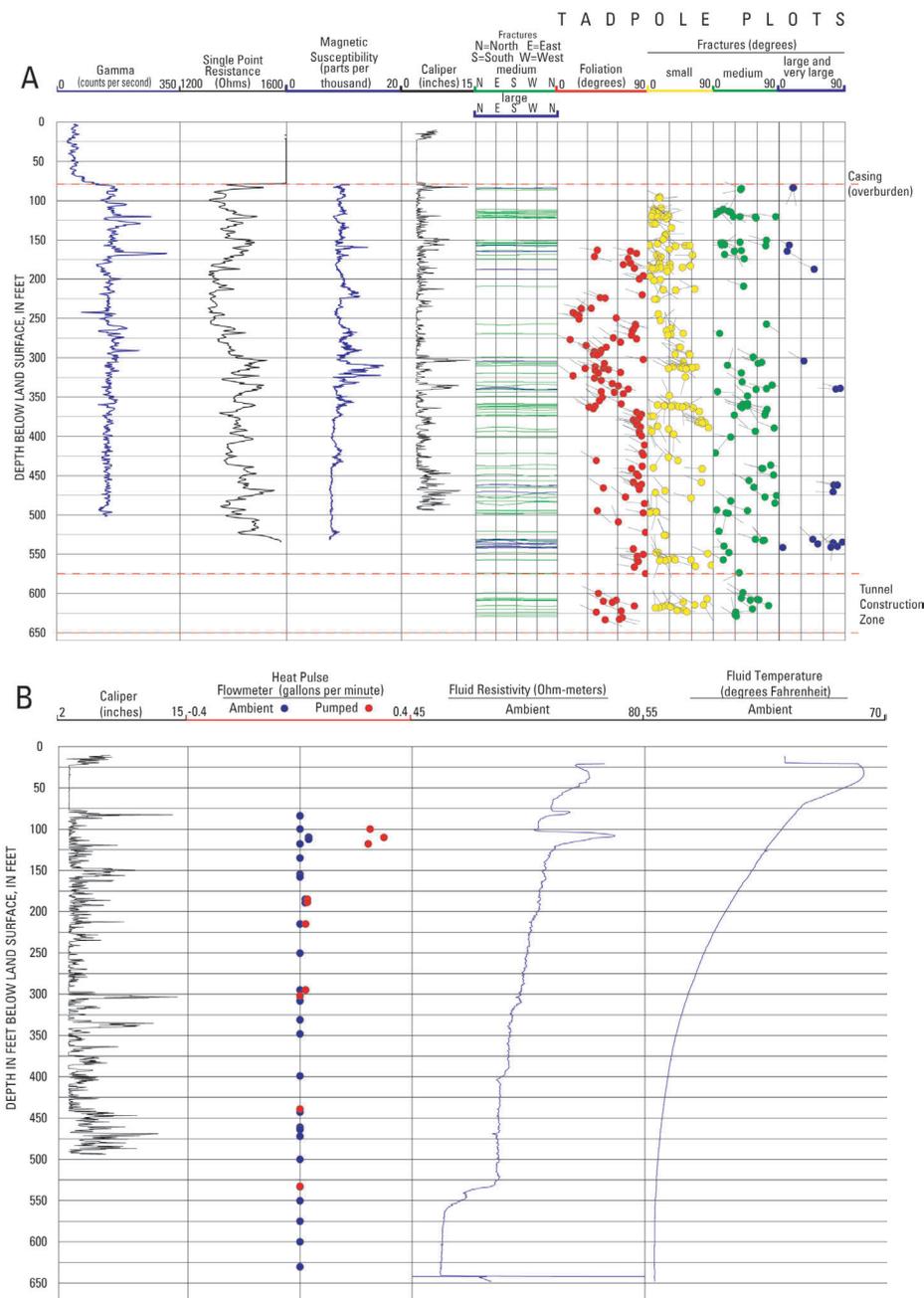


Figure 4. Suite of geophysical logs from borehole GroveST-A (a and b), Manhattan Island, New York.

(0.75 m), or a specific capacity of 1.2 (gal/min)/ft (21 m³/day/m). Total borehole transmissivity was calculated to be 360 ft²/day (33.4 m²/day), which was the highest of the five boreholes.

Borehole W34ST-B

Fractures and Foliation

The ATV and OTV data indicate a total of 271 fractures from below the casing to the bottom of the W34ST-B borehole with a fracture index of 0.44 fracture per foot (0.3 m) of borehole (shown as tadpole plots in Figure 3a). The mean orientation for the 271 fractures is N20°E 17°NW, and N09°W 57°SW for the foliation (both single clusters).

The gamma-log analysis (Figure 3a) indicates fairly uniform gamma counts in the bedrock, except for a few spikes that reflect possible changes in mineralogy. Two zones at 290 to 300 feet (88.4 to 91.4 m) bls and 328 to 335 feet (99.9 to 102.1 m) bls have the lowest resistance and the highest EM conductivity and correlate with two highly fractured transmissive zones (Figure 3a).

Ground Water Flow Zones

The average hydraulic head at W34ST-B was 10.5 feet (3.2 m) elevation. Water-level fluctuations of ~4 feet (1.22 m) during successive field visits over two months indicate possible tidal, pumping, or natural recharge effects.

EM flowmeter, fluid-temperature, fluid-resistivity logs from borehole W34ST-B indicate several depth intervals at which a deflection or change in slope corresponds to transmissive fractures (Figure 3b). Slope changes in these logs are seen at 72, 299, 328 to 330, 355 to 363, and 470 feet (21.9, 91.1, 99.9 to 100.6, 108.2 to 110.6, and 143.3 m) bls (Figure 3b).

Pumping the borehole at a rate of 3 gal/min (16.4 m³/day) for 2.88 hours produced a drawdown of 11.2 feet (3.4 m), or a specific capacity of 0.27 (gal/min)/feet (4.8 m³/day/m). Total borehole transmissivity was calculated to be 75 ft²/day (7 m²/day). EM flowmeter, fluid-temperature, and fluid-resistance logging detected five separate transmissive fracture zones at 72, 299, 328 to 330, 355 to 363, and 470 feet (21.9, 91.1, 99.9 to 100.6, 108.2 to 110.6, and 143.3 m) bls (Figure 3b). Under pumping conditions, ~75% of the borehole's transmissivity corresponds to the 299 feet (91.1 m) bls zone, and ~25% to the 72 feet (22 m) bls zone. Estimated transmissivity values for the 72 feet (22 m) and 299 feet (91.1 m) bls fracture zones were 19 and 56 ft²/day (1.8 and 5.2 m²/day), respectively.

Borehole W26ST-A

Fractures and Foliation

The ATV and OTV indicate a total of 198 fractures were encountered with a fracture index of 0.37 fracture per foot (0.3 m) of open borehole. The mean orientation of the 198 fractures was N08°E 20°W, and the mean foliation orientation was N13°E 61°NW. Several conductive SPR spikes correlated to medium and large ground water producing fractures (Figures 3c and 3d).

Ground Water Flow Zones

The average hydraulic head at borehole W26ST-A was 4.8 feet (1.5 m) elevation. A partial collapse of the borehole at 268 feet (81.7 m) bls prevented the passage of some geophysical probes beyond this depth. The result of this collapse was the lack of delineation of individual fracture transmissivities from 268 feet (81.7 m) bls to the bottom of the borehole. Ambient fluid temperature and fluid resistivity logs indicated potentially transmissive fractures at 48, 70, 231, 266, and 530 feet (14.6, 21.3, 70.4, 81.1, and 161.5 m) bls (Figure 3d).

Pumping the borehole at a rate of 1.5 gal/min (8.2 m³/day) for 2.6 hours produced a drawdown of 11.3 feet (3.4 m), or a specific capacity of 0.13 (gal/min)/ft (2.32 m³/d/m). Total borehole transmissivity was calculated to be 35 ft²/day (3.25 m²/day). Heat-pulse flowmeter, fluid-temperature, and fluid-resistivity logging detected two minor transmissive fractures at 231 and 266 feet (70.4 and 81.1 m) bls with transmissivities of 0.5 ft²/day (0.046 m²/day) each. The fractures between 268 to 567.3 feet (81.7 to 173 m) bls had a transmissivity of 34 ft²/day (3.2 m²/day) or 97% of the total borehole transmissivity.

Borehole GroveST-A

Fractures and Foliation

ATV and OTV data indicate a total of 247 fractures with a fracture index of 0.44 fracture per foot (0.3 m) of borehole from below casing to the bottom of the GroveST-A borehole (Figure 4a). The mean orientation for the 247 fractures was N27°E 25°NW, and N19°E 67°NW for the foliation (both single clusters).

Ground Water Flow Zones

The average hydraulic head at the GroveST-A borehole was 0.4 foot (0.12 m) elevation. Heat-pulse flowmeter, fluid-temperature, and fluid-resistivity logs indicate seven possible transmissive fracture zones at 84, 100, 115, 164, 209, 299, and 530 feet (25.6, 30.5, 35, 50, 63.7, 91.1, and 161.5 m) bls (Figure 4b). Pumping the borehole at a rate of 0.5 gal/min (2.7 m³/day) for 1.4 hours produced a drawdown of 47.3 feet (14.4 m), or a specific capacity of 0.01 (gal/min)/feet (0.15 m³/day/m). Total borehole transmissivity was calculated to be 2.0 ft²/day (0.19 m²/day). Under ambient (nonpumping) conditions, a small amount of upflow was detected from 209 to 164 feet (63.7 to 50 m) fracture zones and from the 115 to 100 feet (35 to 30.5 m) fracture zones (Figure 4b). Under pumping conditions, 74% of the total borehole transmissivity came from the 164 feet bls fracture zone. Transmissivity was estimated for the 84, 100, 115, 164, 209, 299, and 503 feet (25.6, 30.5, 35, 50, 63.7, 91.1, and 161.5 m) fracture zones to be <0.1, 0.1, 0.2, 1.5, 0.1, 0.1, and <0.1 ft²/day, (<0.009, 0.009, 0.019, 0.14, 0.009, 0.009, and <0.009 m²/day), respectively.

Summary

Advanced borehole geophysical techniques were used to delineate the fracture matrix and the individual fracture transmissivity of the bedrock encountered in five test boreholes along the southwestern part of Manhattan Island. The geophysical logs provided data on the bedrock lithology and

major contacts, the location and orientation (true strike and dip) of fractures and foliation, and the hydraulic characteristics of fractures that transmit ground water.

The bedrock contains numerous fractures that intersect the study area. Depth to bedrock ranges from 8 to 80 feet (2.4 to 24 m) bls. Fracture indexes range from 0.25 to 0.44 fracture per foot (0.3 m) of bedrock. Total-borehole fracture populations are either nearly horizontal or moderate-angle dip with a west to northwest dip azimuth. Overall, the average foliation of the bedrock ranges from a southwest to northwest dip azimuth with a 60° dip plunge angle.

Water levels in the fractured bedrock ranged from 29.1 feet (8.9 m) elevation in the northern part of the study area (W55ST-A) to 0.4 foot (0.12 m) elevation in the southern part (GroveST-A). Ground water appears to flow within an interconnected fracture network toward the south and west. Transmissivity values for most transmissive fracture zones in each borehole were determined, if possible. Correlating inflow zones interpreted from heat-pulse flowmeter logs with major fracture zones indicated by other geophysical logs delineated transmissive fracture zones. Each of the five boreholes tested had several transmissive fracture zones, some with moderate transmissivity. Borehole transmissivities ranged from <2 to 360 ft²/day (0.2 to 33 m²/day). No correlation is indicated between borehole fracture index and total transmissivity.

Acknowledgments

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