J. Geophys. Eng. **4** (2007) 245–252 doi:10.1088/1742-2132/4/3/S02

Geohydrologic assessment of fractured crystalline bedrock on the southern part of Manhattan, New York, through the use of advanced borehole geophysical methods

F Stumm[1], A Chu[1], P K Joesten[2] and J W Lane Jr[2]

[1] U S Geological Survey, New York Water Science Center, Coram, NY, USA
[2] U S Geological Survey, Branch of Geophysics, Storrs, CT, USA

E-mail: fstumm@usgs.gov, achu@usgs.gov, pjoesten@usgs.gov and jwlane@usgs.gov

Received 31 August 2006
Accepted for publication 18 January 2007
Published 31 August 2007
Online at stacks.iop.org/JGE/4/245

Abstract

Advanced borehole-geophysical methods were used to assess the geohydrology of fractured crystalline bedrock in 31 of 64 boreholes on the southern part of Manhattan Island, NY in preparation of the construction of a new water tunnel. The study area is located in a highly urbanized part of New York City. The boreholes penetrated gneiss, schist, and other crystalline bedrock that has an overall southwest-to northwest-dipping foliation. Most of the fractures intersected are nearly horizontal or have moderate- to high-angle northwest or eastward dip azimuths. Heat-pulse flowmeter logs obtained under nonpumping (ambient) and pumping conditions, together with other geophysical logs, delineated transmissive fracture zones in each borehole. Water-level and flowmeter data suggest the fractured-rock ground-water-flow system is interconnected. The 60 MHz directional borehole-radar logs delineated the location and orientation of several radar reflectors that did not intersect the projection of the borehole. A total of 53 faults intersected by the boreholes have mean orientation populations of N12°W, 66°W and N11°W, 70°E. A total of 77 transmissive fractures delineated using the heat-pulse flowmeter have mean orientations of N11°E, 14°SE (majority) and N23°E, 57°NW (minority). The transmissivity of the bedrock boreholes ranged from 0.7 to 870 feet squared (ft^2) per day (0.07 to 81 metres squared (m^2) per day).

Keywords: fractured rock, borehole-geophysics, ground-water, Manhattan, geohydrologic

(Some figures in this article are in colour only in the electronic version)

1. Introduction

This study began in 1998 as a cooperative research project between the US Geological Survey (USGS) and the New York City Department of Environmental Protection (NYCDEP) to apply advanced borehole-geophysical methods to provide a comprehensive geologic and hydrologic assessment of the crystalline bedrock in southeastern New York (figure 1). The study provided critical structural and hydrologic data of the bedrock underlying New York City during the planning and construction of a new water tunnel. The study which was completed in a highly urbanized environment demonstrates the advantages of applying advanced borehole-geophysical techniques to engineering problems.

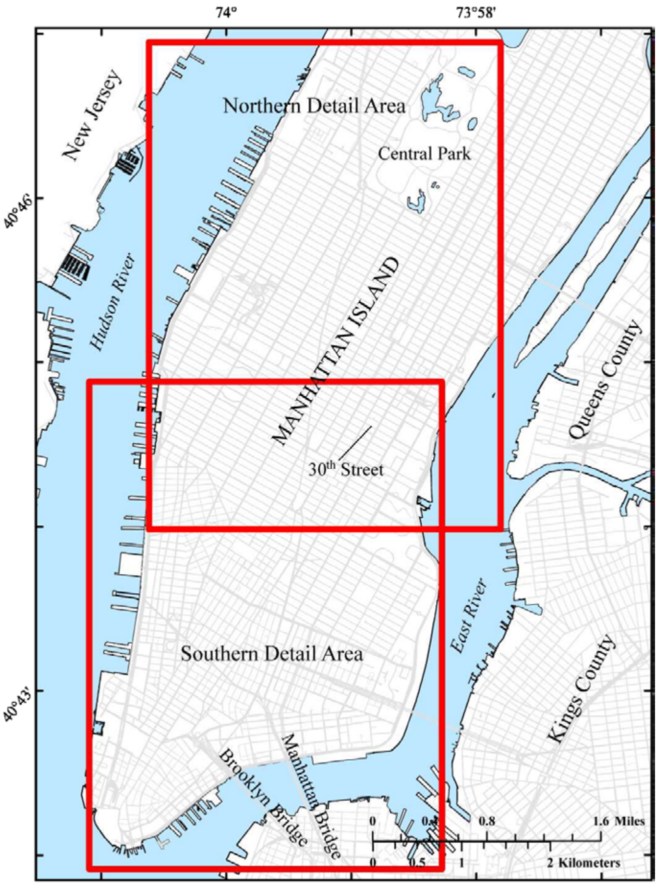

Figure 1. Location of study area, Manhattan Island, New York County, NY.

Manhattan Island is about 12.5 miles (mi) (20.1 kilometres (km)) long and 2 mi (3.2 km) wide (figure 1) and is underlain by unconsolidated deposits ranging from less than 1 ft (0.3 m) thick to more than 250 ft (76 m) thick that overlie metamorphic bedrock (Perlmutter and Arnow 1953). Manhattan Island is bounded on the west by the Hudson River, on the east by the East River and on the south by New York Harbor each containing saltwater (figure 1). The bedrock underlying the study area includes the Manhattan Schist, Hartland Formation, Inwood Marble, Fordham Gneiss and the Ravenswood Granodiorite (Merguerian and Baskerville 1987, Baskerville 1994). Stumm *et al* (2001a and 2004), Stumm and Chowdhury (2003) and Stumm (2005) described the fractured-rock ground-water-flow system in the southern part of Manhattan (northern and southern detail areas) for the first time.

This paper (1) outlines the geophysical logging and methods of analysis used, (2) presents geophysical logs, fracture and foliation data from selected boreholes, (3) summarizes the geophysical interpretations of fractures, faults and foliation in each borehole, (4) describes water levels measured in the boreholes and (5) summarizes the transmissivity of the bedrock, and locations of transmissive fractures in selected boreholes.

2. Methods of data collection and analysis

This study used an array of advanced borehole-geophysical methods and analysis techniques to acquire information about the physical and hydrogeologic properties of the fractured bedrock and unconsolidated glacial deposits. Data collected and analysed during this study included (1) borehole-geophysical logs, (2) geologic structure (foliation, fractures and faults), (3) ground-water levels and (4) transmissivity.

Sixty-four NX-sized (3 inch (in) (7.6 centimetre (cm)) diameter) boreholes were drilled by the diamond-core method to obtain continuous rock-core samples (figure 2). All bedrock boreholes were cased from the land surface through the unconsolidated overburden to the top of the bedrock, and were uncased or open from the bedrock surface to the bottom of the drilled depth. The majority of the boreholes had an average depth of 591 ft (180 m) below land surface (BLS).

2.1. Borehole-geophysical logging

Borehole-geophysical logs collected in this study included natural gamma, single-point-resistance (SPR), short-normal resistivity (*R*), mechanical and acoustic caliper, magnetic susceptibility, borehole-fluid temperature and resistivity, specific conductance (SpC), dissolved oxygen (DO), pH, redox, heat-pulse flowmeter (at eight selected boreholes), borehole deviation, acoustic and optical televiewer (ATV and OTV), and directional borehole radar (at 23 selected boreholes). The logging methods have been described by Keys (1990), Keys and MacCary (1971), McNeill *et al* (1996), Serra (1984), Lane *et al* (2001) and Stumm *et al* (2001b).

A new geophysical probe that collects multiple fluid parameters, herein called the 'QW log', included fluid-temperature, SpC, DO, pH and redox logs; these were used to help delineate transmissive fractures in the boreholes (Stumm *et al* 2004). The QW log complements conventional fluid temperature and resistivity logs that do not always provide definitive information on the locations of transmissive fractures.

2.2. Geologic-structure analysis

Foliation, fractures and faults penetrated in each borehole were delineated from the analysis of OTV and ATV geophysical logs. Fractures were classified as small (0.04 in (1 millimetre (mm)) or less), medium (greater than 0.04 to 0.39 in (greater than 1 to 10 mm)), large (greater than 0.39 to 9.8 in (greater than 10 mm to 25 cm)) or very large (greater than 9.8 in (greater than 25 cm)), depending on the apparent aperture or width of the opening. Fracture and foliation orientations were plotted as tadpoles in figure 3; the tadpole tail points to the dip azimuth and the circle indicates the dip angle. Borehole-radar analysis was used to (1) verify the assumption that most fractures extend beyond the borehole, (2) detect major fractures or faults as far as 90 ft (27 m) from the borehole that may not intersect any borehole in the area and would otherwise have been missed and (3) delineate the orientation (strike and dip) of these distant fractures or faults.

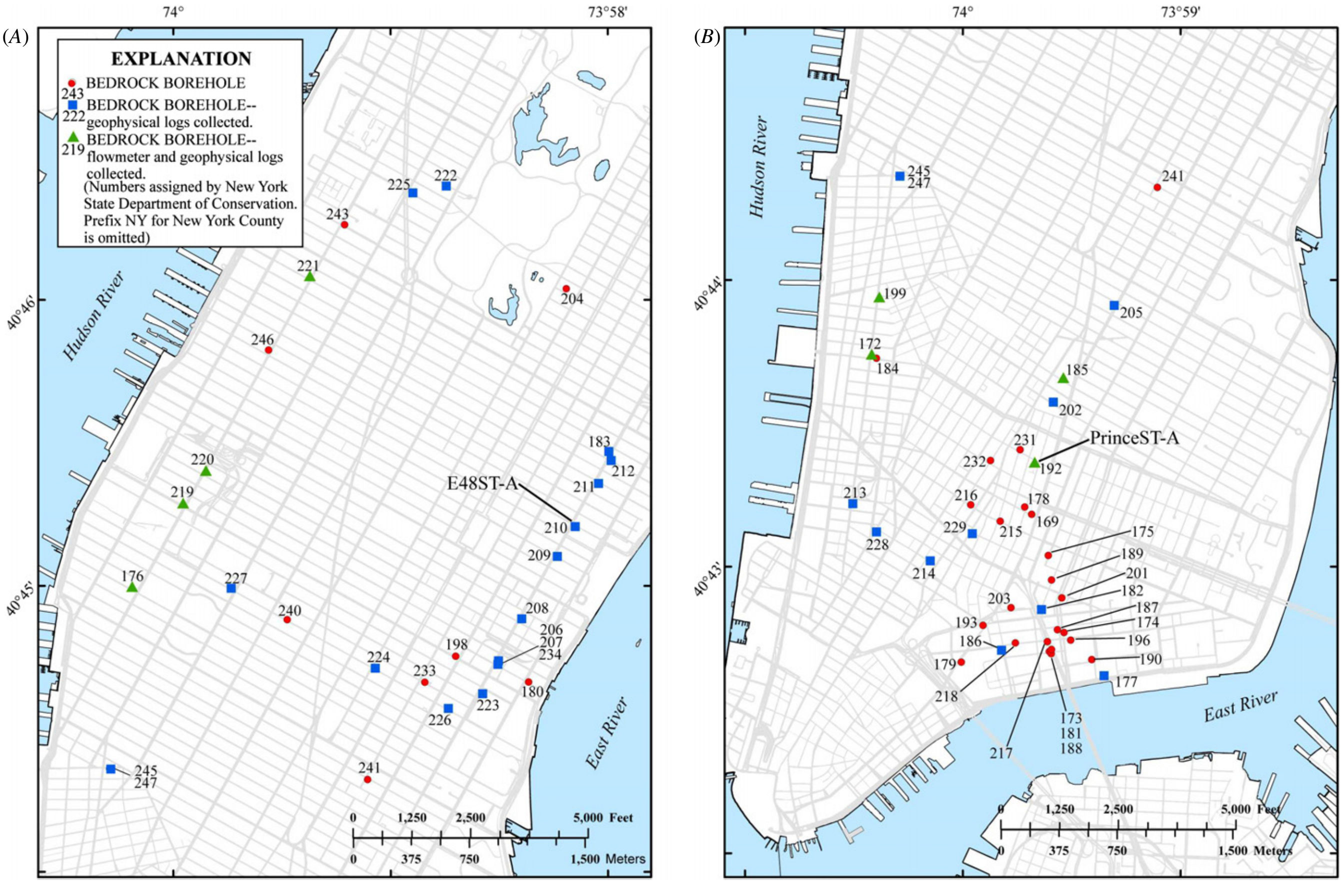

Figure 2. Locations of bedrock boreholes within the study area, Manhattan Island, NY.

2.3. Geohydrologic analysis

Fluid-temperature and SpC logs were collected at 31 boreholes under ambient conditions. Flowmeter logs were collected at eight boreholes (NY-185, NY-221, NY-220, NY-219, NY-176, NY-199, NY-172 and NY-192) during ambient and pumping conditions (figure 2). Data from specific-capacity pumping tests at 59 boreholes were applied to a computer program (Bradbury and Rothschild 1985) to calculate the specific capacity and transmissivity of the entire borehole.

2.4. Ground-water levels

Ground-water flows through the non-porous bedrock through an interconnected network of fractures and faults. Ground-water levels were measured during borehole-geophysical logging, water-level synoptics and specific-capacity tests at all 64 bedrock boreholes.

2.5. Transmissivity

The flowmeter logs were analysed through the techniques of Paillet (1998, 2000), whereby differences between flow values at adjacent fracture zones in each borehole were attributed to measurement scatter and a possible net difference in borehole flow. Inflow or outflow at several depth intervals at each borehole is measured; each of these intervals coincides with a fracture, or sets of fractures. In accordance with the techniques of Molz *et al* (1989) and Paillet (2000), the effects of hydraulic-head differences between zones are eliminated by analysing flow under ambient and pumping conditions.

3. Geohydrologic assessment

A total of 64 bedrock boreholes were drilled within the study area (figure 2). Of these, 31 bedrock boreholes have had extensive borehole-geophysical logging and analysis completed.

3.1. Geophysical and geohydrologic analyses of selected wells

Full geophysical, structural and hydrologic interpretations are presented in this paper for two boreholes (E48ST-A (NY-210) and PrinceST-A (NY-192)) as an example of what had been completed at all 31 boreholes (figure 2).

3.1.1. E48ST-A (NY-210). The E48ST-A borehole was selected as an example of a borehole where the heat-pulse flowmeter was not used. The bedrock consisted of schistose gneiss with pegmatite zones at 184 to 196 (56.1 to 59.7 m), 345 to 351 (105.2 to 107 m), 373 to 379 (113.7 to 115.5 m) and 385 to 415 (117.3 to 126.5 m) ft below land surface (BLS).

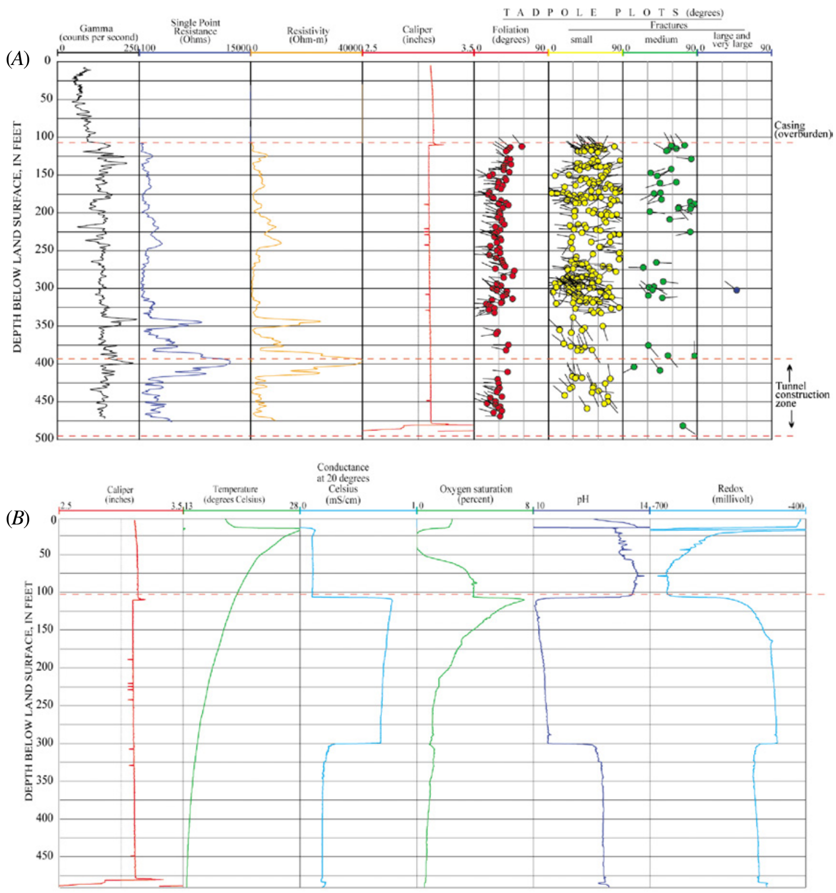

Figure 3. Suite of borehole geophysical logs from E48ST-A (NY-210) ((*A*) and (*B*)) and PrinceST-A (NY-192) ((*C*) and (*D*)), Manhattan Island, NY (continued over page).

Potentially transmissive fractures were delineated using the QW log. The borehole has 105 ft (32 m) of casing and extends 490 ft (149 m) BLS in fractured bedrock.

Fractures and foliation. OTV and ATV logs detected a total of 308 fractures that were plotted on a southern hemisphere projection (figure 3). Most fractures (87 per cent) were small, some were medium and one was large. Analysis of the borehole-radar data indicates that most medium and large fractures extend at least 90 ft (27 m) away from the borehole. The borehole radar also imaged a possible large fracture or fault that would have been intersected by the borehole had it been drilled to 553 ft (168.5 m) BLS. This radar reflector has an orientation of N10°W, 49°NE. Two borehole fracture populations were indicated, one dipping northwestward, the other dipping eastward (figure 4). The total borehole mean foliation orientation was N13°E, 03°NW (figure 5).

The gamma log was fairly uniform throughout the borehole except when pegmatite was intersected at 345 to 350 ft (105.2 to 106.7 m) and 380 to 480 ft (115.8 to 146.3 m) BLS (figure 3(*A*)). The SPR and R logs indicate a large increase in bedrock resistivity from 340 to 420 ft (104 to 128 m) BLS that reflects a lithologic change from gneiss and schist to pegmatite (figure 3).

Ground-water-flow zones. Hydraulic head elevation in E48ST-A borehole was 12.26 ft (3.74 m) above sea level. The QW log indicated possible transmissive fractures at 110, 160, 285, 300 and 480 ft (33.5, 48.8, 86.9, 91.4 and 146.3 m) BLS, where deflections or slope changes were observed (figure 3). The 110 ft (33.5 m) BLS and the 300 ft (91.4 m) BLS zones correlate to medium and large fractures, respectively (figure 3). Analysis of the specific-capacity test data indicated that the E48ST-A borehole has a specific capacity of 0.04 gallons per minute per foot ((gal min^{-1})/ft) (0.5 litres per minute per metre ((L min^{-1})/m)) and a transmissivity of 11 ft squared per day (ft^2/day) (1.0 m squared per day (m^2/day)).

3.1.2. PrinceST-A (NY-192). The PrinceST-A borehole has 120 ft (36.6 m) of casing and extends 665 ft (202.7 m) BLS uncased in fractured bedrock. This borehole was selected as an example of highly fractured bedrock with moderate transmissivity in the south-central part of the study area (figure 2).

Fractures and foliation. Analysis of the OTV and ATV log data indicated that 504 fractures were penetrated by the borehole. The majority of the fractures were small and medium in size (figure 3). A large fracture and gouge zone was detected at 235 ft (71.6 m) BLS. Two borehole fracture populations were indicated; one was northwestward, the second was southeastward (figure 4). The total borehole mean foliation orientation was N42°E, 60°NW (figure 5).

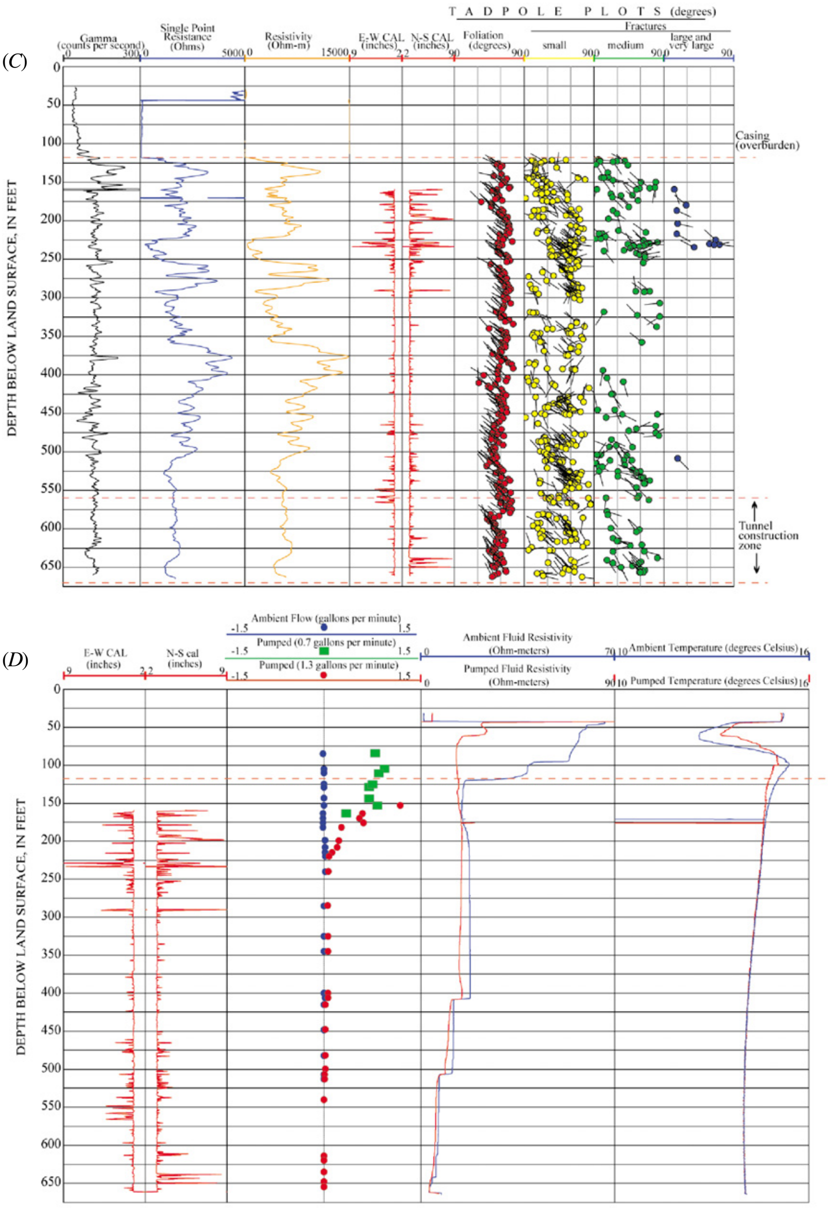

Figure 3. (Continued.)

Borehole-radar logging imaged five potentially large fractures or faults away from the borehole (figure 6). One feature is nearly vertically adjacent to the borehole with an estimated orientation of N10°E, 85°SW. The other four features, which also did not intersect the borehole, have orientations of N30°E, 58°SE; N20°E, 63°SE (figure 6); N70°E, 67°SE; and N70°W, 53°NE.

The unconsolidated glacial deposits have a lower gamma response than the underlying bedrock (figure 3). A decrease in SPR and R log response below 510 ft (155.4 m) BLS correlates to a lithologic change. Most of the large resistivity spikes correlate to pegmatite zones (figure 3).

Ground-water-flow zones. Hydraulic head in the PrinceST-A borehole was 4.52 ft (1.4 m) elevation in November 2004. Fluid temperature and fluid resistivity logs have slope changes indicating a possible leaky casing at 100 ft (30.5 m) BLS and potentially transmissive fractures at 120, 162, 407, 507, 615, 640 and 650 ft (36.6, 49.4, 124, 154.5, 187.4, 195.1 and 198.1 m) BLS (figure 3). Specific-capacity test analysis indicated the PrinceST-A borehole has a specific capacity of 0.32 (gal min^{-1})/ft (4.0 (L min^{-1})/m) and a transmissivity of 90 ft^2/day (8.4 m^2/day).

Heat-pulse flowmeter logging in the borehole under ambient and pumping conditions indicated transmissive fractures at 162, 230, 407, 507 and 615 ft (49.4, 70.1, 124, 154.5 and 187.4 m) BLS (figure 3). Analysis of the ambient and pumping flowmeter data indicates that the fractures at 162, 230, 407 and 507 ft (49.4, 70.1, 124 and 154.5 m) BLS have estimated transmissivities of 83, 2, 3 and 2 ft^2/day (7.7, 0.2, 0.3 and 0.2 m^2/day), respectively. The transmissivity of the zone at 615 ft (187.4 m) BLS was not determined and is probably below the detection limit of the flowmeter.

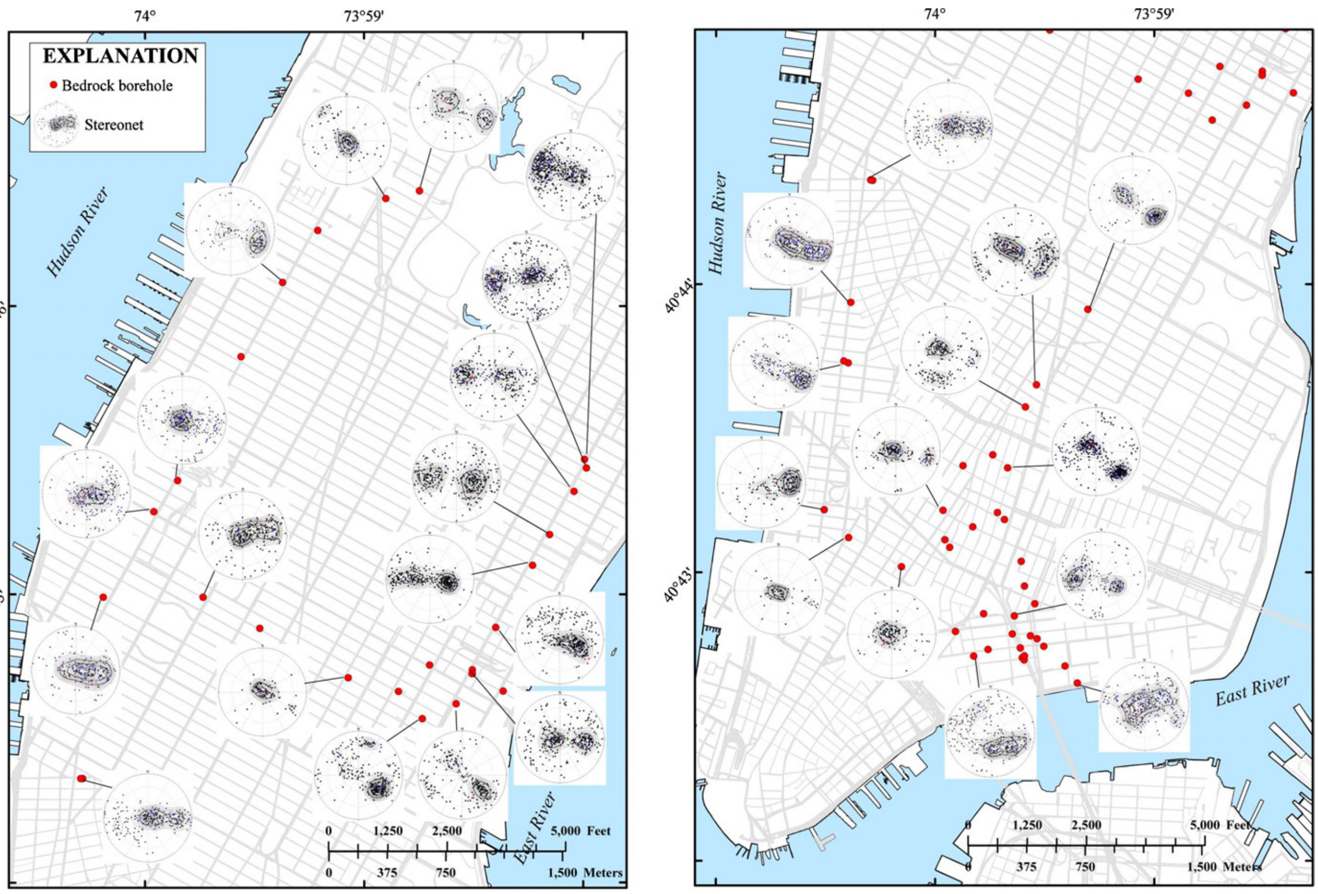

Figure 4. Fracture orientation in boreholes within the study area, Manhattan Island, NY (stereonets are plotted as poles to planes).

3.2. Faults, fractures and foliation

All 31 OTV-analysed borehole stereonets were plotted. Most of the fractures measured in the study area have subhorizontal population clusters and a secondary population cluster that is moderately dipping towards the northwest (figure 4).

A total of 208 large fractures were delineated in the 31 boreholes logged with the OTV. Stereonet analysis of the large fractures indicates that most are part of a subhorizontal population cluster with a mean orientation of N43°E, 07°SE and a smaller secondary population cluster dipping toward the northwest.

Several major northwest-to southeast-trending faults have been mapped in Manhattan (Berkey 1910, Baskerville 1994). A total of 53 faults were delineated with two major population clusters, one with a mean orientation of N12°W, 66°W and the other with a mean orientation of N11°W, 70°E.

Analysis of the foliation data indicates that orientation of the foliation in the study area dips northwest to southwest, with foliation dip angles in the range of 30° to 70° (figure 5). Foliation appears to be somewhat horizontal in the northeasternmost part of the study area and gradually increases in dip angle with an azimuth of northwest to southwest (figure 5).

3.3. Water levels and transmissive fractures

Water levels were measured periodically in all open boreholes from 1998 to 2005. The water levels range from 64.7 ft (19.7 m) elevation at NY-222 to −42.8 ft (−13.0 m) elevation at NY-226. The water levels suggest that ground-water flows from the recharge area in the northernmost part (the area near Central Park) towards the southern, eastern and western coastal discharge zones (figure 1).

Heat-pulse flowmeter logging was completed at eight boreholes (NY-185, NY-221, NY-220, NY-219, NY-176, NY-199, NY-172 and NY-192) (figure 2). A total of 77 transmissive fractures were delineated at the eight boreholes. Stereonet analysis of these transmissive fractures indicates two population clusters of fractures, one with a mean orientation of N11°E, 14°SE and the other with a mean orientation of N23°E, 57°NW. These data suggest that the fractured-rock ground-water-flow system in southern Manhattan is dominated by subhorizontal fractures and fractures that dip moderately to the northwest.

3.4. Bedrock transmissivity

A total of 59 bedrock boreholes had specific-capacity test data analysed for total borehole transmissivity. The bedrock transmissivity ranged from 0.7 to 870 ft^2/day (0.07 to 81 m^2/day) in the study area. The majority of boreholes (69 per cent) had transmissivities less than 100 ft^2/day (9.3 m^2/day).

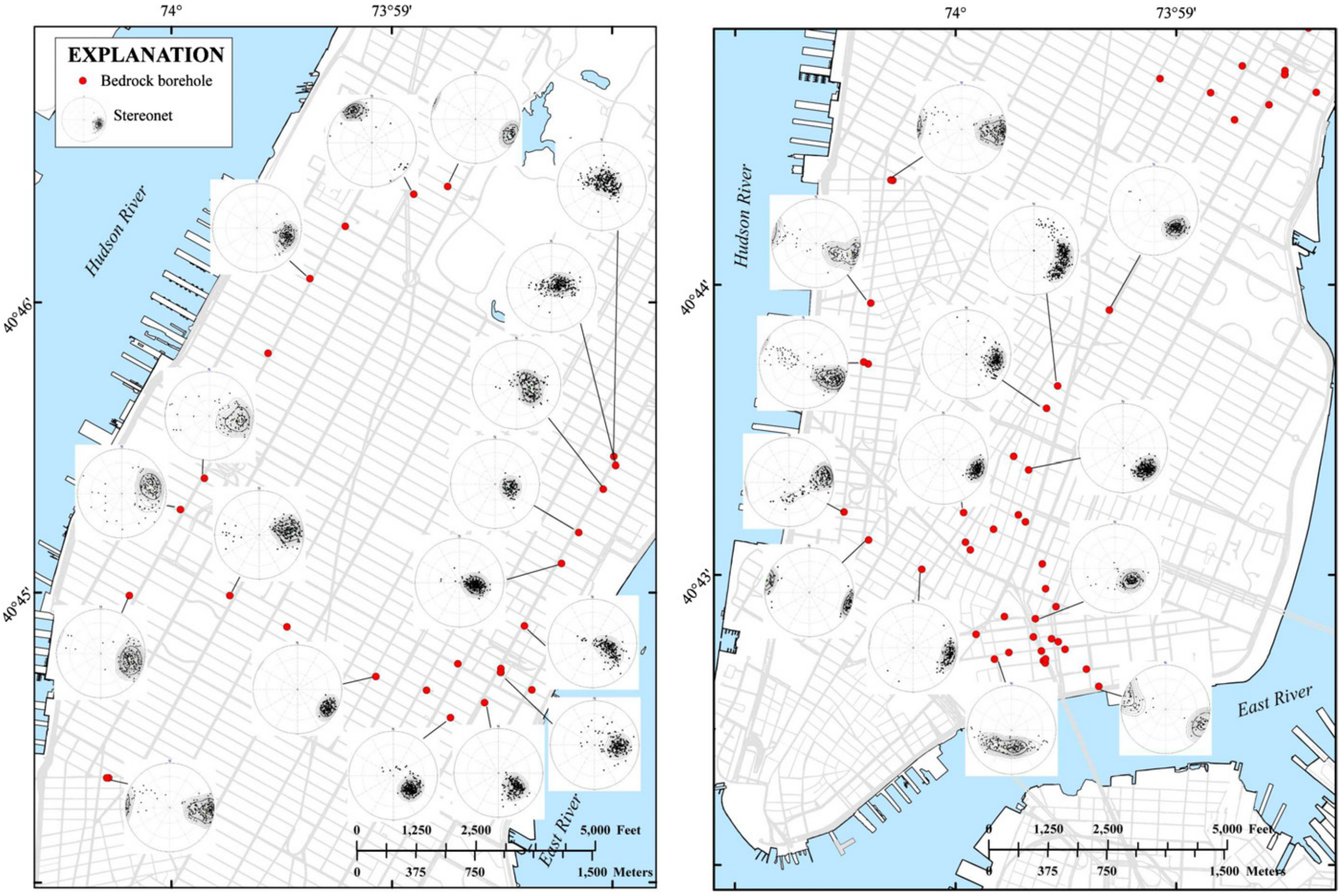

Figure 5. Foliation orientation in boreholes within the study area, Manhattan Island, NY (stereonets plotted as poles to planes).

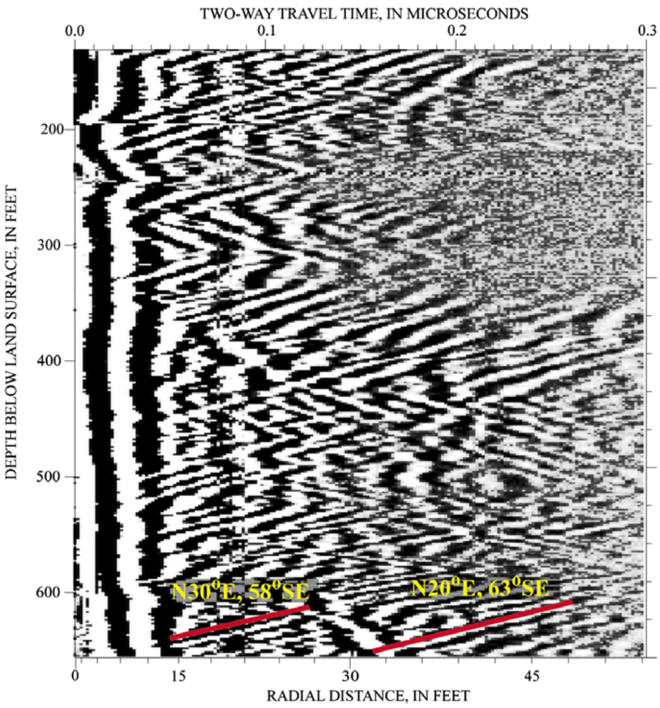

Figure 6. Directional borehole-radar reflection image showing selected reflectors, PrinceST-A borehole (NY-192), Manhattan Island, NY.

4. Conclusions

Borehole-geophysical techniques were used in 31 boreholes in southern Manhattan, New York, to determine geologic and hydrologic characteristics of the bedrock. The gamma, SPR, R and QW logs were used to delineate changes in bedrock lithology, and in some cases, transmissive fractures. The OTV log was most useful in delineating the strike and dip of fractures and foliation. In some boreholes fluid-temperature and fluid-resistivity logs were used to delineate transmissive fractures; however, a new QW probe provided superior fluid-parameter logs and appeared to detect fractures with lower transmissivities than the standard temperature/resistivity logs. The heat-pulse flowmeter log was used to delineate specific fractures that were transmissive and determine their transmissivity.

All boreholes penetrated moderately fractured bedrock that contained medium and large fractures. Most fractures delineated by the OTV log are subhorizontal in the study area. Stereonet analysis indicates two large fracture population clusters, one subhorizontal and the second moderately dipping to the northwest. A total of 53 faults were delineated in the 31 boreholes. Foliation was fairly consistent throughout the study area with dip azimuths ranging from northwest to southwest and dip angles ranging from 30° to 70°.

Water-level and flowmeter data suggest the fractured-rock ground-water-flow system is interconnected. Stereonet analysis indicates the 77 transmissive fractures in the study area are either subhorizontal with a mean orientation of N11°E, 14°SE or northwest dipping with a mean of N23°E, 57°NW. The transmissivity of the boreholes ranged from 0.7 to 870 ft^2/day (0.07 to 81 m^2/day) in the study area.

Acknowledgments

The authors thank the personnel of the NYCDEP for technical assistance, support and access to their boreholes. The authors also wish to acknowledge the technical assistance of the personnel of the USGS Office of Ground Water, Branch of Geophysics and the use of the borehole radar system.

References

Baskerville C A 1994 Bedrock and engineering geologic maps of New York County and parts of Kings and Queens Counties, New York *US Geological Survey Miscellaneous Investigations Series* Map I-2306, 2 sheets, scale 1:24,000

Berkey C P 1910 Areal and structural geology of southern Manhattan Island *Ann. New York Acad. Sci.* **19** 247–82

Bradbury K R and Rothschild E R 1985 A computerized technique for estimating the hydraulic conductivity of aquifers from specific-capacity data *Groundwater* **23** 240–6

Keys W S 1990 Borehole geophysics applied to water-resources investigations *US Geological Survey Techniques of Water Resources Investigations* book 2, chapter E2, p 150

Keys W S and MacCary L M 1971 Application of borehole geophysics to water-resources investigations *US Geological Survey Techniques of Water Resources Investigations* book 2, chapter E1, p 126

Lane J W Jr, Joesten P K, Pohll G and Mihevic T 2001 Analysis of borehole-radar reflection logs from selected HC boreholes at the Project Shoal Area, Churchill County, Nevada *US Geological Survey Water Resources Investigations Report 01-4014* p 23

McNeill J D, Hunter J A and Bosner M 1996 Application of a borehole induction magnetic susceptibility logger to shallow lithological mapping *J. Environ. Eng. Geophys.* **0** 77–90

Merguerian C and Baskerville C A 1987 The geology of Manhattan Island and the Bronx, New York City, New York *Northeastern Section of the Geological Society of America (*Centennial Fieldguide*)* ed D C Roy vol 5 pp 137–40 (p 481)

Molz F J, Morin R H, Hess A E, Melville J G and Guven O 1989 The impeller meter for measuring aquifer permeability variations—evaluation and comparison with other tests *Water Resour. Res.* **25** 1677–83

Paillet F L 1998 Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations *Water Resour. Res.* **34** 997–1010

Paillet F L 2000 A field technique for estimating aquifer parameters using flow log data *Ground Water* **38** 510–21

Perlmutter N M and Arnow T 1953 Ground water in Bronx, New York, and Richmond Counties with summary data on Kings and Queens Counties, New York City, New York *US Geological Survey Ground Water Bulletin* GW-32, p 86

Serra O 1984 *Fundamentals of Well-Log Interpretation* (New York: Elsevier) p 423

Stumm F, Chu A and Lange A D 2001a Use of advanced borehole geophysical techniques to delineate fractured-rock ground-water flow, faults, foliation and fractures along the western part of Manhattan, New York *US Geological Survey Open-File Report 01-196* p 46

Stumm F *et al* 2001b Use of advanced borehole geophysical techniques to delineate fractured-rock ground-water flow and fractures along water-tunnel facilities in northern Queens County, New York *US Geological Survey Water Resources Investigations Report 00-4276* p 12

Stumm F and Chowdhury S 2003 Delineation of ground water flow in fractured rock in the southwestern part of Manhattan, New York, through use of advanced borehole geophysical methods *Groundwater Monit. Remediat.* **23** 42–9

Stumm F, Chu A and Monti J Jr 2004 Delineation of faults, fractures, foliation, and ground-water-flow zones in fractured rock, on the southern part of Manhattan, New York, through use of advanced borehole geophysical techniques *US Geological Survey Open-File Report 04-1232* p 212

Stumm F 2005 Delineation of the fractured-rock and unconsolidated overburden ground-water flow systems on the southern part of Manhattan, New York, through use of advanced borehole-geophysical techniques *PhD Dissertation* City University of New York Graduate Center, New York, p 144