DELINEATION OF STRUCTURE AND GROUND-WATER-FLOW ZONES IN BEDROCK, ON THE SOUTHERN PART OF MANHATTAN, NEW YORK, THROUGH USE OF ADVANCED BOREHOLE-GEOPHYSICAL TECHNIQUES

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Abstract

Advanced borehole-geophysical techniques were used to assess the geohydrology of crystalline bedrock in 26 of 29 boreholes on the southern part of Manhattan Island, N.Y., in preparation for construction of a third water tunnel for New York City. The borehole-logging techniques included natural gamma, single-point resistance, short-normal resistivity, mechanical and acoustic caliper, magnetic susceptibility, borehole-fluid temperature and resistivity, borehole-fluid specific conductance, dissolved oxygen, pH, redox, heat-pulse flowmeter (at selected boreholes), borehole deviation, acoustic and optical televiewer, and borehole radar (at selected boreholes). Hydraulic head and specific-capacity test data were collected from 29 boreholes. The boreholes penetrated gneiss, schist, and other crystalline bedrock that has an overall southwest to northwest-dipping foliation. Most of the fractures penetrated are nearly horizontal or have moderate- to high-angle northwest or eastward dip azimuths. Fracture population dip azimuths are variable. Heat-pulse flowmeter logs obtained under pumping and nonpumping (ambient) conditions, together with other geophysical logs, indicate transmissive fracture zones in each borehole. The 60-megahertz directional borehole-radar logs delineated the location and orientation of several radar reflectors that did not intersect the projection at nine selected boreholes.

Fracture indexes range from 0.12 to 0.93 fractures per foot of borehole. Analysis of specific-capacity tests from each borehole indicated that transmissivity ranges from 1 to 459 feet squared per day.

Introduction

Manhattan Island is about 12.5 mi long and 2 mi wide (figure 1) and consists of unconsolidated deposits ranging from less than 1 ft thick to more than 200 ft thick overlying metamorphic bedrock. 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 (figure 1).

Twenty-nine boreholes were drilled during 1999-2004 to identify the type of rock and its degree of fracturing in the boreholes at the proposed tunnel depths (500 to 900 ft below land surface). Oriented structural information, borehole deviation, and hydraulic properties of the boreholes could not be determined by the non-oriented cores.

In 1998, the U.S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection (NYCDEP), began a study to apply advanced borehole geophysical methods to provide a comprehensive geologic and hydrologic assessment of the crystalline bedrock in southeastern New York. These techniques were applied at 26 of the 29 boreholes in southern Manhattan to identify (1) the bedrock lithology and major contacts, (2) the location and orientation (true strike and dip) of fractures, and foliation of the rock intersected by the boreholes, (3) the hydraulic characteristics of transmissive fracture zones, and (4) major fractures or faults that lie as much as 90 ft beyond the borehole (at nine selected boreholes). Transmissive (ground- water producing) fractures that may be

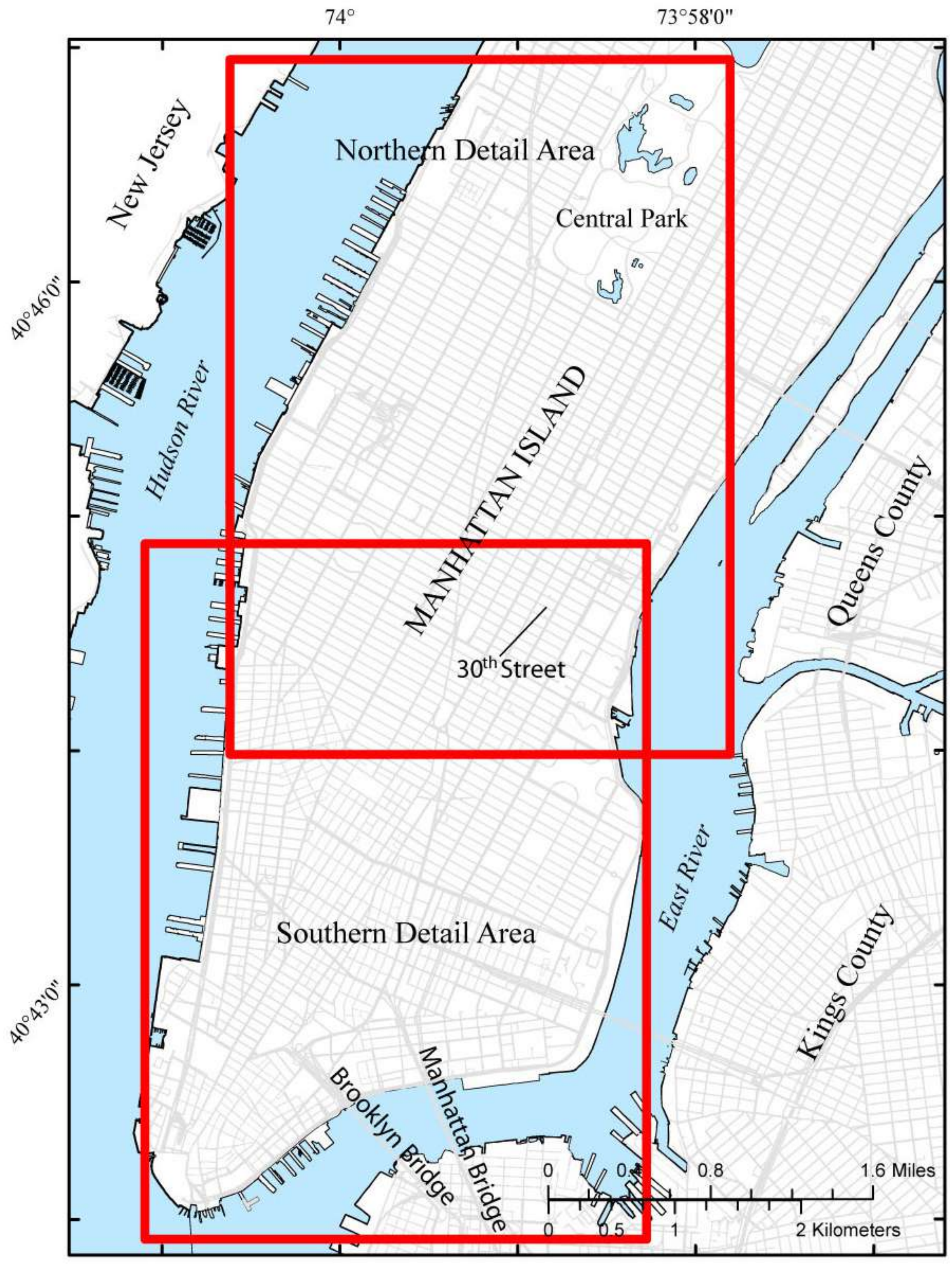

Figure 1: Southern Manhattan study area with northern and southern detail study areas, Manhattan Island, New York County, N.Y.

intersected by the tunnel excavation could produce large quantities of ground-water flow into the tunnel.

Borehole Network

Twenty-nine NX-sized (3-in diameter) boreholes were drilled by the diamond-core method to obtain continuous rock-core samples. All bedrock boreholes are cased from land surface through the unconsolidated overburden to the top of bedrock, and are uncased from the bedrock surface to the bottom of the drilled depth. Due to availability, only 26 of 29 boreholes were geophysically logged.

Hydrogeology

Southern Manhattan is underlain by high-grade metamorphic bedrock consisting of a sequence of gneiss and schistose-gneiss interlayered with granite (Baskerville, 1992). The bedrock contains many fractures, some of which are transmissive. Depth to bedrock ranges from less than 1 to over 250 ft below land surface (BLS) within the southern part of Manhattan.

METHODS

Borehole-Geophysical Logging

Borehole-geophysical logs collected in this investigation included natural gamma, single-point-resistance (SPR), short-normal resistivity (R), mechanical and acoustic caliper, magnetic susceptibility (MAG), borehole-fluid temperature and resistivity, borehole specific conductance, dissolved oxygen (DO), pH, redox, heat-pulse flowmeter, borehole deviation, acoustic and optical televiewer (ATV and OTV), and directional borehole radar (Chu and Stumm, 2004; Stumm and others, 2001; 2004).

Geologic-Structure Analysis

Foliation, fractures, and faults penetrated in each borehole were delineated from the analysis of OTV and ATV geophysical log analysis. Fractures were classified as small, medium, large, or very large, depending on the apparent aperture or width of the opening. Borehole-radar analysis at nine selected boreholes: (1) verified the assumption that most fractures extend beyond the borehole, (2) detected major fractures or faults as far as 90 ft from the borehole that may not intersect any borehole in the area and would otherwise have been missed, and (3) delineated the orientation (strike and dip) of these distant fractures or faults. A fracture index is calculated for each borehole.

Foliation

Foliation analyses, grouped by depth, indicate populations with similar dip azimuths and dip angles. Foliation in each borehole was measured using OTV data. Analysis of the variations in foliation orientations in each borehole and within the study area included tadpole and stereonet plots (figures 2 and 3).

Fractures

Fracture analysis identifies populations with similar dip azimuths and dip angles. Analysis of the variations in fracture orientations in each borehole and within the study area included tadpole and stereonet plots (figures 4 and 5). Gouge-zones are defined as highly altered or weathered rock zones indicative of either mechanical or chemical weathering or weakening of the bedrock. Gouge-zones are typically found in the OTV log data and analyzed as fractures in the particular borehole’s fracture index and stereonet analysis.

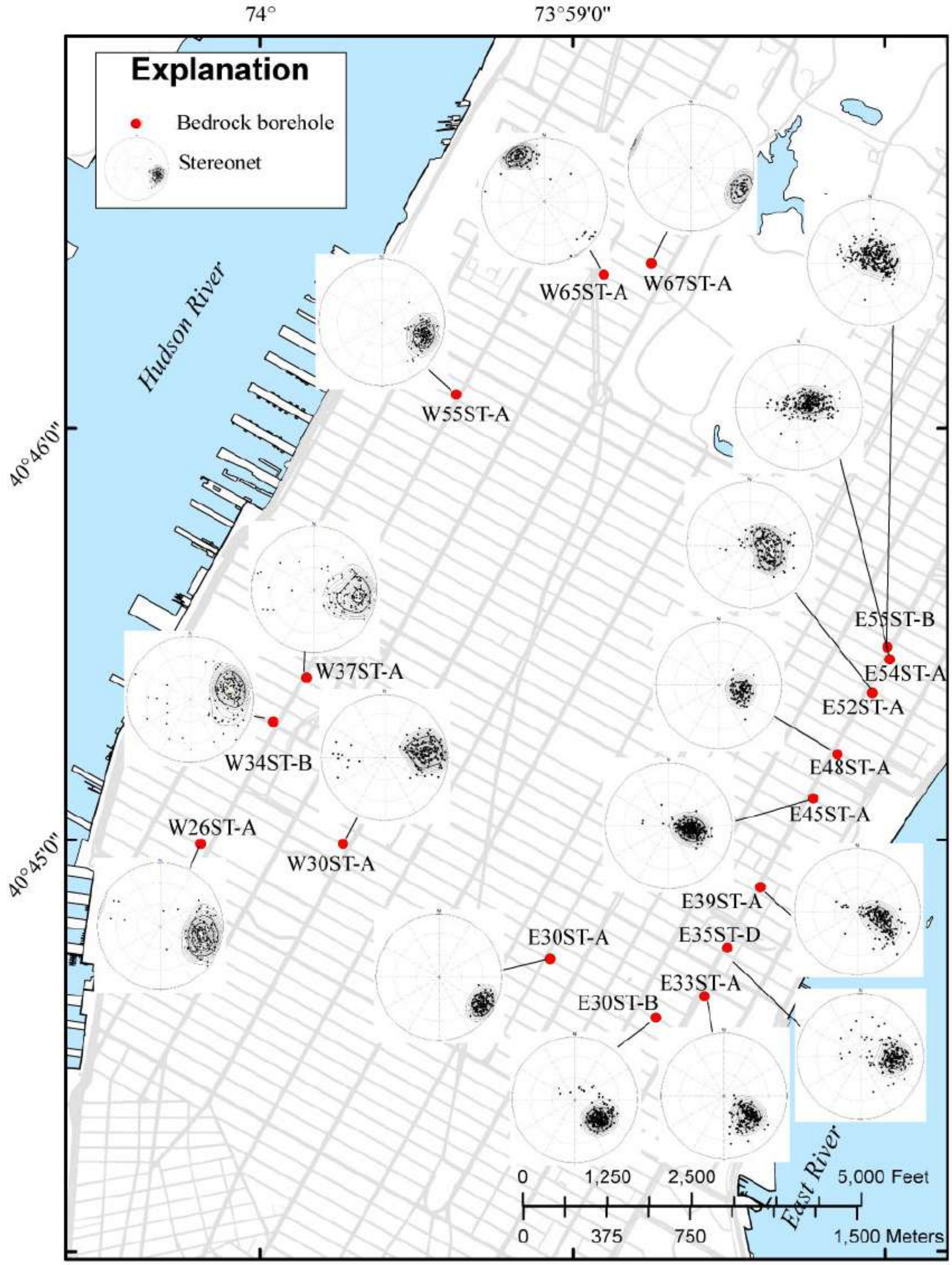

Figure 2: Bedrock borehole foliation, northern detail area, Manhattan Island, N.Y. (Stereonets are plotted as poles to planes).

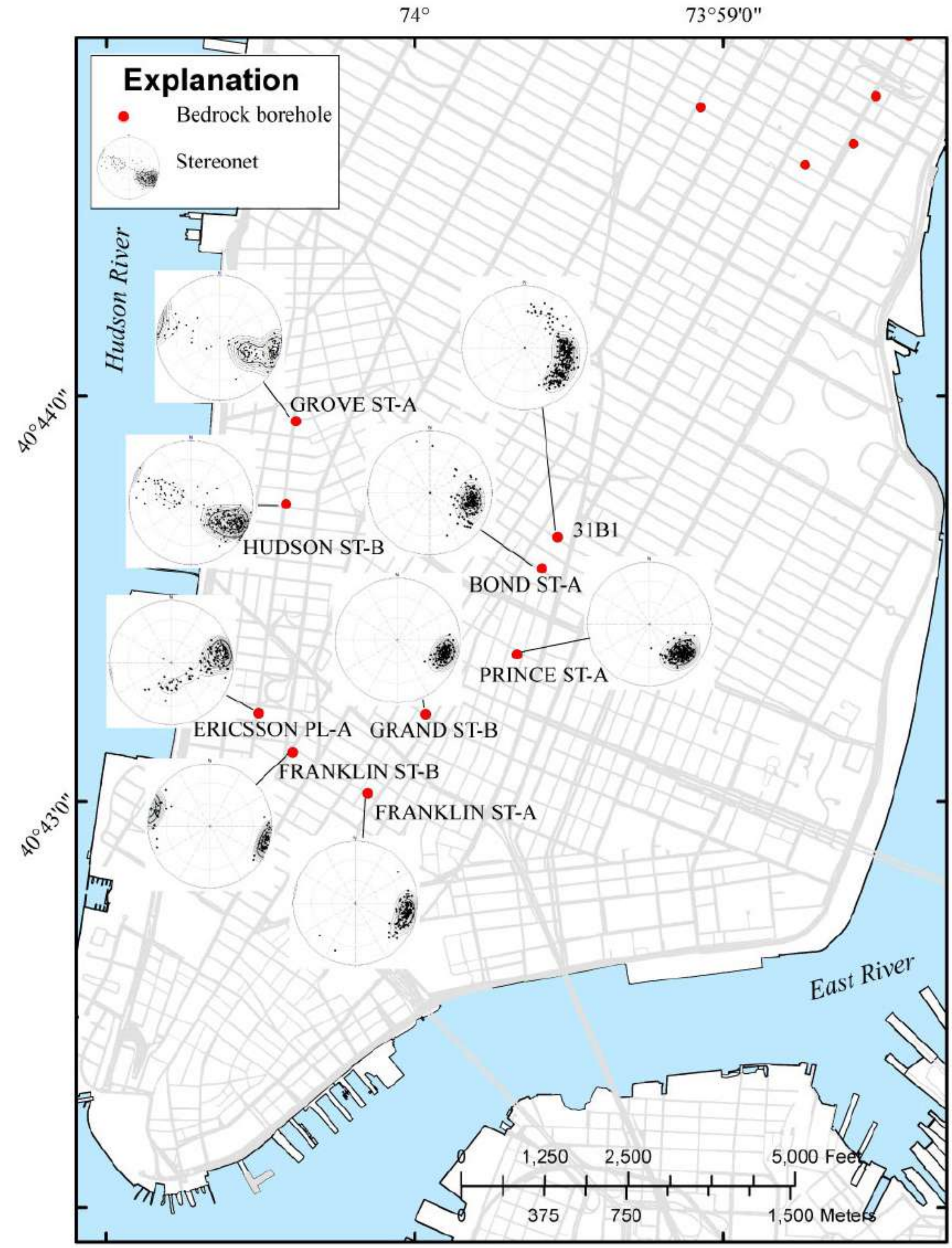

Figure 3: Bedrock borehole foliation, southern detail area, Manhattan Island, N.Y. (Stereonets are plotted as poles to planes).

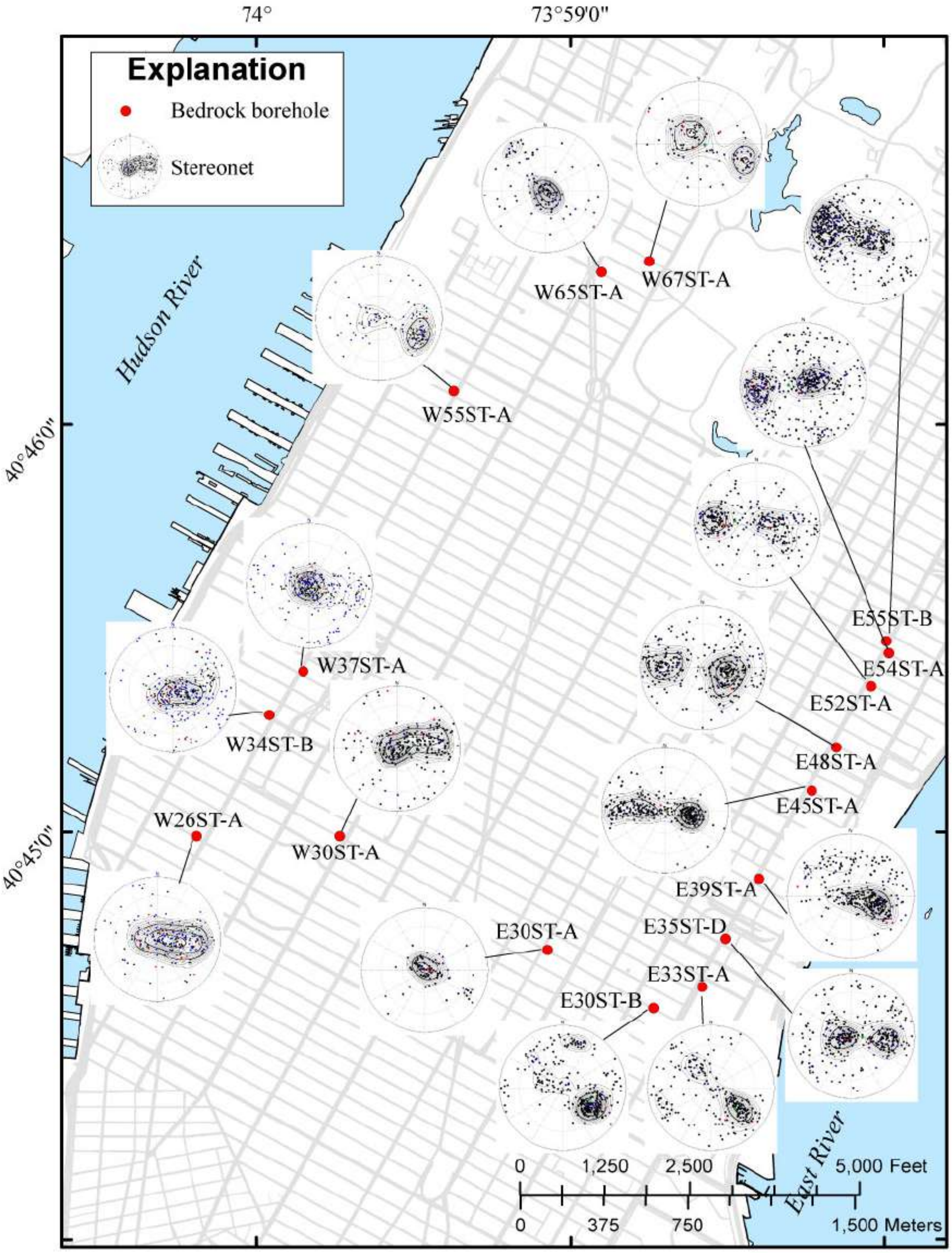

Figure 4: Bedrock borehole fractures, northern detail area, Manhattan Island, N.Y. (Stereonets are plotted as poles to planes).

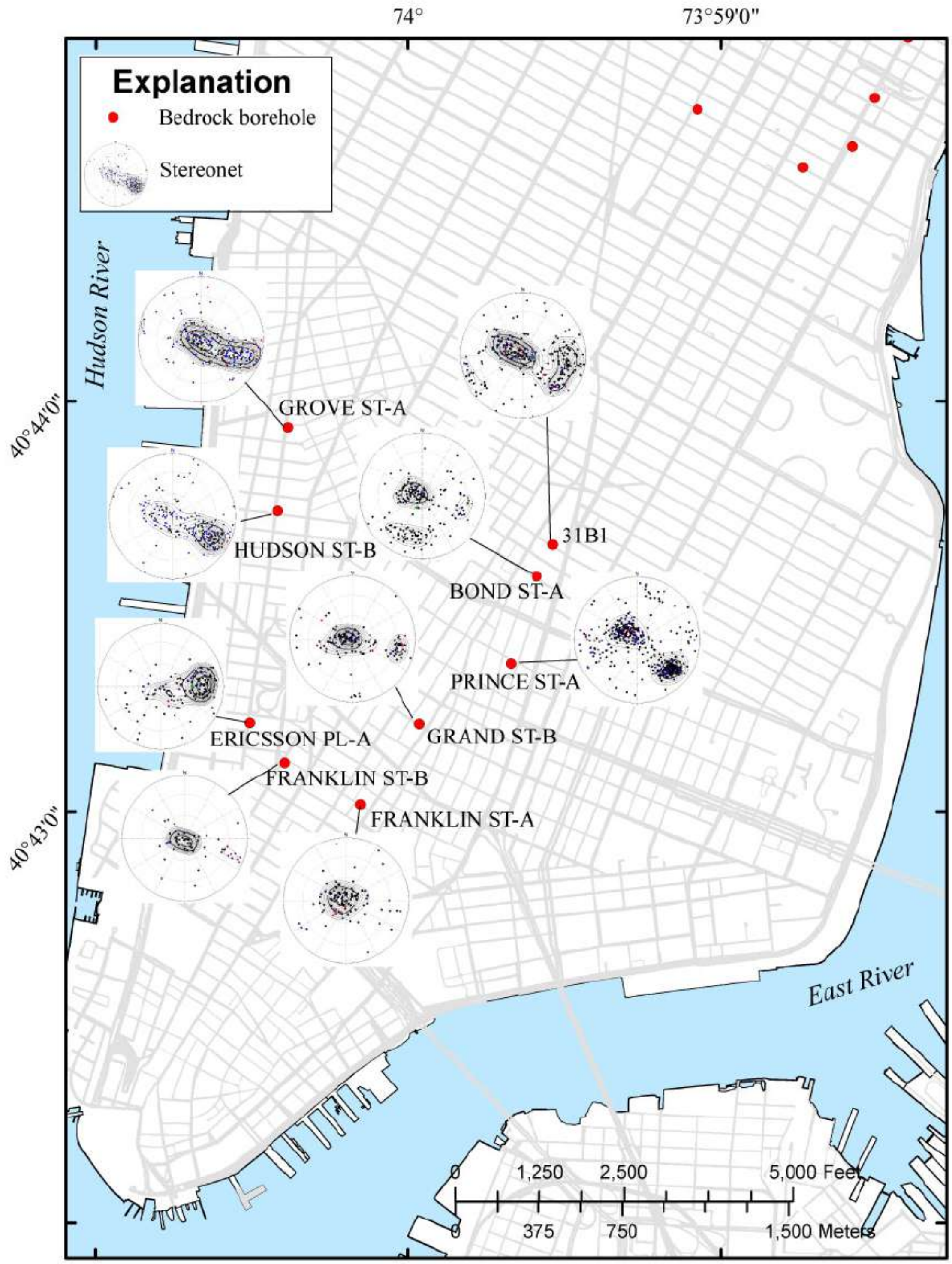

Figure 5: Bedrock borehole fractures, southern detail area, Manhattan Island, N.Y. (Stereonets are plotted as poles to planes).

Faults

OTV logs were carefully examined for evidence of offset or past movement along a fracture. A fracture is classified as a fault if there is evidence of offset or past movement along it. However, all faults were plotted as fractures and factored in the fracture index and stereonet analysis for a given borehole.

Ground-Water-Flow Analysis

Ground-water levels were measured at all 29 boreholes during field visits from April 1999 through April 2004. Fluid-temperature and fluid-specific conductance logs were collected at 26 boreholes during ambient conditions. Flowmeter logs were collected at selected boreholes during ambient and pumping conditions. Measurements of the drawdown, pumping rate, and total pumping time at 28 boreholes during test pumping were applied to a computer program (Bradbury and Rothschild, 1985) to calculate specific capacity and transmissivity of the entire borehole.

A new geophysical tool herein called the "fluid parameter log" included fluid-temperature, fluid specific conductance (SpC), DO, pH, and redox logs, which were used to help delineate transmissive fractures within the boreholes. The conventional fluid temperature and resistivity logs do not always provide information on transmissive fracture locations. Abnormal temperature gradients can be caused by ground-water flow into or out of fractures intersected by the boreholes (Keys, 1990; Williams and Conger, 1990). Changes in water quality also may occur at transmissive fractures and by expanding the measurement parameters, changes in SpC, pH, DO and redox can be detected and more transmissive fractures can be delineated.

Transmissivity

Calculated transmissivity values for the boreholes ranged from 1 to 459 ft^2/d. The transmissive fracture network is a discrete system that is not correlated specifically with the fracture index.

The flowmeter logs were analyzed through techniques of Paillet (1998, 2000), whereby differences between flow values at adjacent fracture zones within each borehole were 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. 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 and others (1989) and Paillet (2000), the effects of hydraulic-head differences between zones can be eliminated by analyzing flow under ambient and pumping conditions.

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

Faults, fractures, and foliation were interpreted from OTV, ATV, borehole-radar, gamma, SPR, R, MAG and caliper logs. Typically, the gamma log response did not show many changes and is uniform throughout the boreholes. Anomalies in the gamma log correlating to fractures or lithologic changes are mentioned in the borehole geophysical log description. SPR and R log responses are variable with depth and correlated to either fracture density or slight lithologic or mineralogic changes in the bedrock (Chu and Stumm, 2004; Stumm and others, 2001; 2004).

The ATV, OTV, and borehole-radar analysis indicate that all boreholes penetrate moderately fractured rock that contains highly fractured zones. Every borehole contains medium and (or) large open fractures that are transmissive. Structural trends of these geologic units and borehole radar logs (at selected boreholes) indicate that most fractures and faults detected in each borehole may extend beyond each borehole. The gamma, SPR, R, fluid-temperature, fluid resistivity, specific conductance, DO, pH, and redox logs detected some of the fracture zones.

Two boreholes FranklinST-B and PrinceST-A were selected to show the geophysical logs collected and analyzed at most boreholes. The FranklinST-B borehole has 86 ft of casing and extends 555 ft BLS (-543.6 ft elevation). The borehole is uncased in fractured bedrock.

OTV analysis indicated a total of 58 fractures within the borehole and a fracture index of 0.12, which is the lowest of any southern Manhattan borehole analyzed. The fractures were predominantly small and medium. Two of these large fractures (at 549 and 550 ft BLS) were considered gouge zones. The foliation is nearly vertical in this borehole, with the highest dip angles measured of any southern Manhattan borehole. The SPR and R logs indicated a slight increase in rock resistivity with depth and delineated all large fractures and some medium fractures as low-resistivity zones (figures 6a and b).

The hydraulic head in FranklinST-B was -0.5 ft elevation. The borehole is within a local cone of depression. The fluid parameter logs indicated changes in slope at 95, 125, and 475 ft BLS (figure 6a). The DO log indicated increases in oxygen concentrations below 150 ft BLS, possibly due to steeply dipping fractures carrying shallow sources of ground water that may have intersected the large fractures penetrated by the borehole. Specific-capacity test analysis indicate the FranklinST-B borehole has a specific capacity of 0.59 (gal/min)/ft and the total borehole transmissivity is calculated to be 170 ft^2/d.

The PrinceST-A borehole has 120 ft of casing and extends 665 ft BLS (-618 ft elevation). Analysis of the OTV and ATV log data indicated 504 fractures were penetrated within the borehole. The PrinceST-A borehole has a fracture index of 0.92. The majority of the fractures were small and medium in size. A large fracture and gouge zone is detected at 235 ft BLS, with an orientation of N28ºE 39ºNW.

Borehole radar logging imaged five potentially large fractures or faults away from the borehole. The overburden sediment has lower gamma response than that of the bedrock below (figure 6b).

The hydraulic head in the PrinceST-A borehole was 4.3 ft above sea level. Fluid temperature and fluid resistivity logs have slope changes indicating a possible leaky casing at 100 ft BLS and potentially transmissive fractures at 120, 162, 407, 507, 615, 640, and 650 ft BLS (figure 6b). Specific-capacity test analysis indicated the PrinceST-A borehole has a specific capacity of 0.32 (gal/min)/ft and a transmissivity of 90 ft^2/d. Heat-pulse flowmeter logging within the borehole under ambient and pumping conditions indicated slight ambient upflow from 615 to 162 ft BLS (figure 6b). Transmissive fractures were delineated with the flowmeter at 162, 230, 407, 507, and 615 ft BLS. Analysis of the ambient and pumping flowmeter data indicate the fractures at 162, 230, 407, and 507 ft BLS have estimated transmissivities of 83, 2, 3, and 2 ft^2/d, respectively. The transmissivity of the zone at 615 ft BLS was not determined and is probably below the detection limit of the flowmeter.

The highest foliation dip angles were found in the southernmost part of the study area. A gradual decrease in dip angles from westward to eastward and from southward to northward is indicated in the central part of the study area. Foliation dip angles in the northwesternmost part of the study area are about 75˚.

No general correlation between fracture orientation and depth is evident in the study area. Total borehole fracture-population orientations are (1) nearly horizontal, and (2) moderate- to high-angle dip with a west-to-northwest dip azimuth. Dipole fracture populations were detected in the seven boreholes (E35ST-D, E39ST-A, E45ST-A, E48ST-A, E52ST-A, E54ST-A, and E55ST-B) boreholes. Fractures in the northwesternmost part of the study area were dominated by sub-horizontal orientations. Many fractures were detected throughout the study area with dip angles in excess of 70˚. Analysis of the 60-MHz directional radar at nine boreholes indicated strong radar reflectors that are probably fractures that,

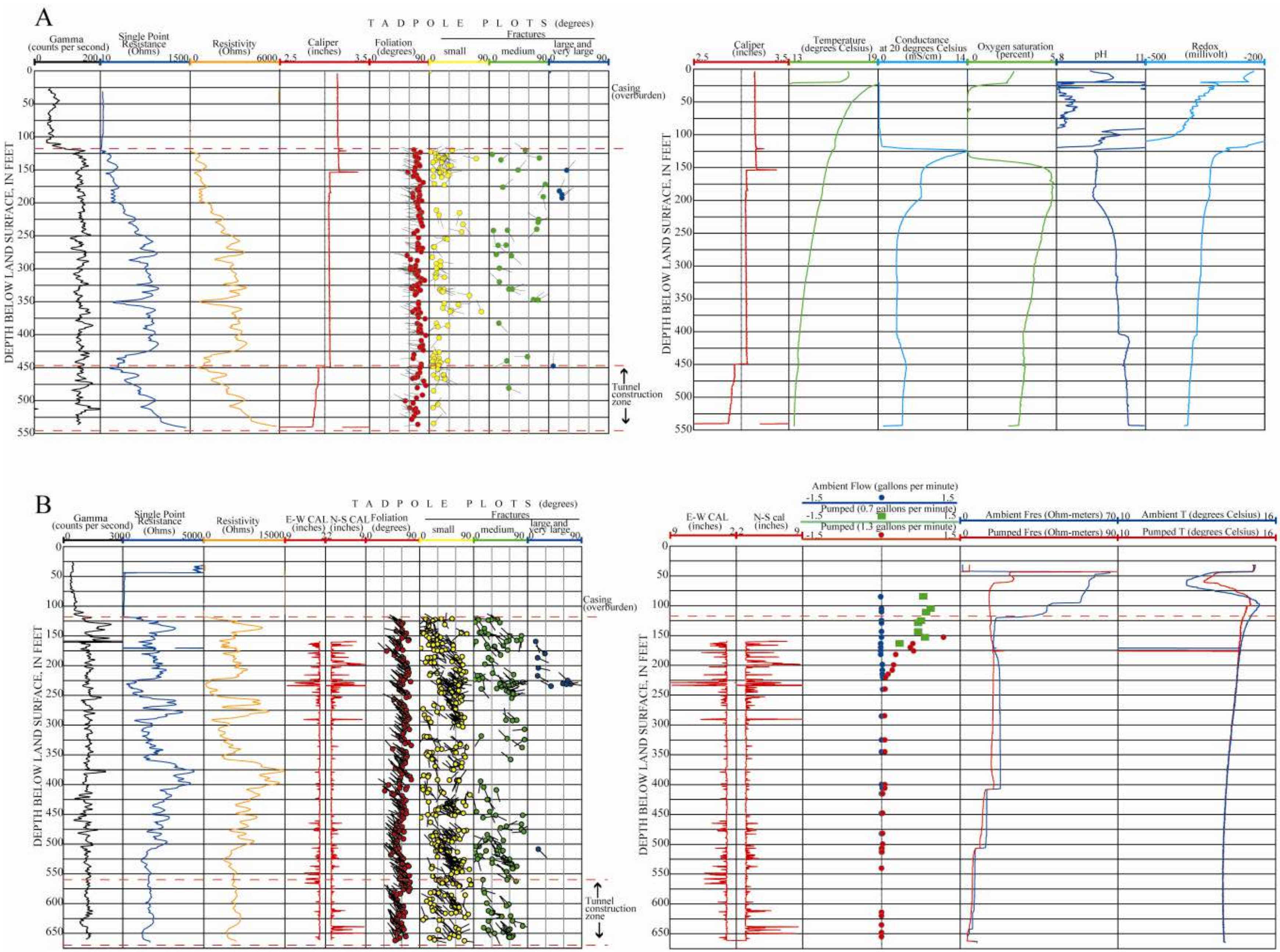

Figure 6: Suite of borehole geophysical logs from boreholes **A.** FranklinST-B, and **B.** PrinceST-A, Manhattan Island, N.Y.

if transmissive, could produce appreciable quantities of ground-water to flow. Faults were detected in sixteen of the twenty-six geophysically logged boreholes.

Water levels in the fractured bedrock are highest in the north-central part of the study area (58 and 66 ft elevation), and lowest in the southern and coastal areas. Analysis of the distribution of hydraulic head in Manhattan indicate the fractured-rock ground-water flow system is a continuum of interconnected, transmissive fractures, and that with areas of recharge (highest head) are in the north-central part of the study area, and areas of discharge (lowest head) along the coastline and southern end. The lowest water levels (-23 ft elevation) are in boreholes in the eastern-central part of the island. This area consists of a large cone of depression or series of depressions due to the pumping of shallow railway tunnels. The ground-water divide generally follows the central spine of southern Manhattan Island.

Conclusions

Twenty-nine boreholes on the southern part of Manhattan Island were drilled to provide cores, geophysical logs, and geotechnical information. In 1998, the USGS, in cooperation with the NYCDEP, began a study to apply advanced borehole-geophysical methods to assess the hydrogeology of the crystalline bedrock in southeastern New York including Manhattan Island.

The geophysical logs provided data on the location and orientation (dip azimuth and dip) of fractures (Optical and Acoustic televiewers), the orientation (dip azimuth and dip) of rock foliation (Optical Televiewer), locations of contacts between rock units of differing lithology, and locations of possible transmissive (water-producing) fractures. The geophysical logs also provided information on the magnetic susceptibility, electrical resistivity and resistance of the bedrock, the direction and quantity of ground-water flow within the borehole, resistivity, temperature, specific conductance, dissolved oxygen, pH, and redox of ground water, a profile of the borehole diameter, and the extent of fractures or geologic features up to 90 ft beyond the borehole.

The bedrock beneath the southern part of Manhattan contains numerous fractures. Depth to bedrock ranges from less than 1 to more than 250 ft below land surface. Unconsolidated sediments overlie the bedrock and were cased in the open boreholes. Stereonet and tadpole analyses were used to identify foliation and fracture relations.

Some of the boreholes have large transmissive fractures that may produce appreciable quantities of ground-water flow. Fracture indices range from 0.12 to 0.93 fractures per foot of bedrock. No correlation is indicated between fracture orientation and depth. Total-borehole fracture population dip azimuths are somewhat variable throughout the study area, with east or northwest azimuths in the northeastern part; northwest, southwest, and west in the central part; and southwest, northwest, west, and northeast in the southernmost part of the study area.

The average foliation of the bedrock ranges from southwest to northwest dip azimuth. Foliation in the northeastern part have common strikes with dip angles of about 75° dipping toward the northwest. Foliation in the central part dips toward the northwest to west. Foliation dip angles ranged from 70° in the southwestern part to less than 15° and sub-horizontal along the southeasternmost part of the study area. Foliation dip azimuths in the southernmost part of the study area are northwest to westward.

Analysis of the 60-Mhz directional radar at nine selected boreholes indicated strong radar reflectors, which probably are fractures that extend beyond the boreholes and would intersect the boreholes if the boreholes were deeper. Radar analysis indicated that some of these fractures, if water bearing, could produce appreciable quantities of ground-water flow.

Water levels measured quarterly from April 1999 to April 2004 in the fractured bedrock indicated a recharge zone in the central-northern part of the study area and discharge zones along the coastlines and southern parts. Two large cones of depression were detected, one in the eastern midtown area, and the other in the southwestern part of the island. Total borehole transmissivity values ranged from 1 to 459 ft^2/d. Transmissive fracture zones were delineated by correlating inflow zones interpreted from heat-pulse flowmeter logs with major fracture zones indicated by other geophysical logs. Each of the twenty-six boreholes that were geophysically logged had several transmissive fracture zones. Some of these fractures have high transmissivity, especially at those boreholes with moderate to high total borehole transmissivity.

References

Baskerville, C.A., 1992, Bedrock and engineering geologic maps of Bronx County and parts of New York and Queens Counties, New York: U.S. Geological Survey Miscellaneous Investigations Series, map I-2003, 2 sheets, scale 1:24,000.

Bradbury, K.R., and Rothschild, E.R., 1985, A computerized technique for estimating the hydraulic conductivity of aquifers from specific-capacity data; Groundwater, v. 23, no. 2, p. 240-246.

Chu, A., and Stumm, F., 2004, Hydrogeologic interpretation of advanced borehole geophysical logs in fractured rock along planned water-tunnel facilities in New York City, *in* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 22-26, 2004, Colorado Springs, Colorado: Environmental and Engineering Geophysical Society, p. 1148-1151.

Keys, W.S., 1990, Borehole geophysics applied to water-resources investigations: U.S. Geological Survey Techniques of Water Resources Investigations, book 2, chap. E2, 150 p.

Molz, F.J., Morin, R.H., Hess, A.E., Melville, J.G., and Guven, Oktay, 1989, The impeller meter for measuring aquifer permeability variations—evaluation and comparison with other tests: Water Resources Research, v. 25, no. 7, p. 1677-1683.

Paillet, F. L., 1998, Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations: Water Resources Research, v. 34, no. 5, p. 997-1010.

Paillet, F. L., 2000, A field technique for estimating aquifer parameters using flow log data: Ground Water, v. 38, no. 4, p. 510-521.

Stumm, F., Chu, A., and Lange, A.D., 2001, 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; U.S. Geological Survey Open-File Report, 2001-196, 46 p.

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; U.S. Geological Survey Open-File Report, 2004-1232, 212 p.

Williams, J.H., and Conger, R.W., 1990, Preliminary delineation of contaminated water-bearing fractures intersected by open-hole bedrock wells: Groundwater Monitoring and Review, v. 10, no. 4, p. 118-126.

Acknowledgments

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