Section 2: Area Geology

This section presents an overview of the subsurface conditions in the NYC watershed region, including evaluation of gas-producing potential, description of rock strata and geologic features, analysis of water resources, and a summary of data provided by tunnel construction records.

2.1 Shale Gas Potential and the NYC Watershed

The Marcellus formation is one of a series of "stacked" Appalachian plays that also include the Utica Shale. These formations underlie an area of approximately 95,000 square miles[7] that extends from eastern Kentucky, through West Virginia, Ohio and Pennsylvania and into southern/central New York. The Marcellus formation is estimated to contain 200 to 500 trillion cubic feet (tcf) of total natural gas reserves and is considered one of the largest potential sources of developable energy in the U.S.[8]

In New York, the Marcellus formation (Figure 2-1) lies beneath all or part of 29 counties and the entirety of the 1,585 square miles of NYC's West-of-Hudson watersheds. The maximum depth (ca. 6,500 feet) occurs along the Delaware River at the New York - Pennsylvania border, and the formation is shallowest to the east and north. The NYC watershed area is underlain by relatively thick areas of the Marcellus formation that are estimated to have relatively high gas production potential. Within the West-of-Hudson watersheds, 1,076 square miles are not protected and are subject to gas exploration and development activities. This area represents less than six percent of the approximately 18,700 square miles of the Marcellus formation that are in New York State.

Analysis of the depth, thickness, organic content, thermal maturity, and other characteristics of the Marcellus formation has been performed as part of an ongoing study by the New York State Museum.[9] Figure 2-1, which is drawn from the New York State Museum study, shows the approximate depth to the top of the Marcellus formation (top portion) and the approximate thickness of the formation (lower portion). The dotted contours also indicate the transformation ratio associated with the formation, which is an estimate of the thermal maturity of the organic material.[10] The higher the ratio, the more gas that is potentially available.

While acknowledging uncertainties that prevent precise delineation of areas with the highest gas production potential, the authors of the study suggest that drilling in New York is likely to start in the thickest and deepest areas of the formation, which includes southern Tioga, Broome, Delaware and Sullivan Counties, which border the northeast corner of Pennsylvania, before progressing north and west. These areas are also attractive for gas production because of their proximity to the Millennium pipeline and other regional natural gas transmission infrastructure.

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[7] ALL Consulting, Groundwater Protection Council. (2009). *Modern Shale Gas Development in the United States: A Primer.* Prepared for: U.S. Dep't of Energy Office of Fossil Energy and National Energy Technology Laboratory.

[8] Navigant Consulting, Inc. (2008). *North American Natural Gas Supply Assessment*, Prepared for: American Clean Skies Foundation.

[9] Smith, T. and J. Leone. New York State Museum. *Integrated Characterization of the Devonian Marcellus Shale Play in New York State*. Presented at the Marcellus Shale Gas Symposium of the Hudson-Mohawk Professional Geologists' Association, April 29, 2009. Accessed from www.hmpga.org/Marcellus_presentations.html.

[10] Transformation ratio refers to the percentage of Kerogen (an organic solid, bituminous mineraloid substance) occurring in the unit, that has been destructively converted to oil or gas by ambient geological forces (i.e., pressure, temperature) .

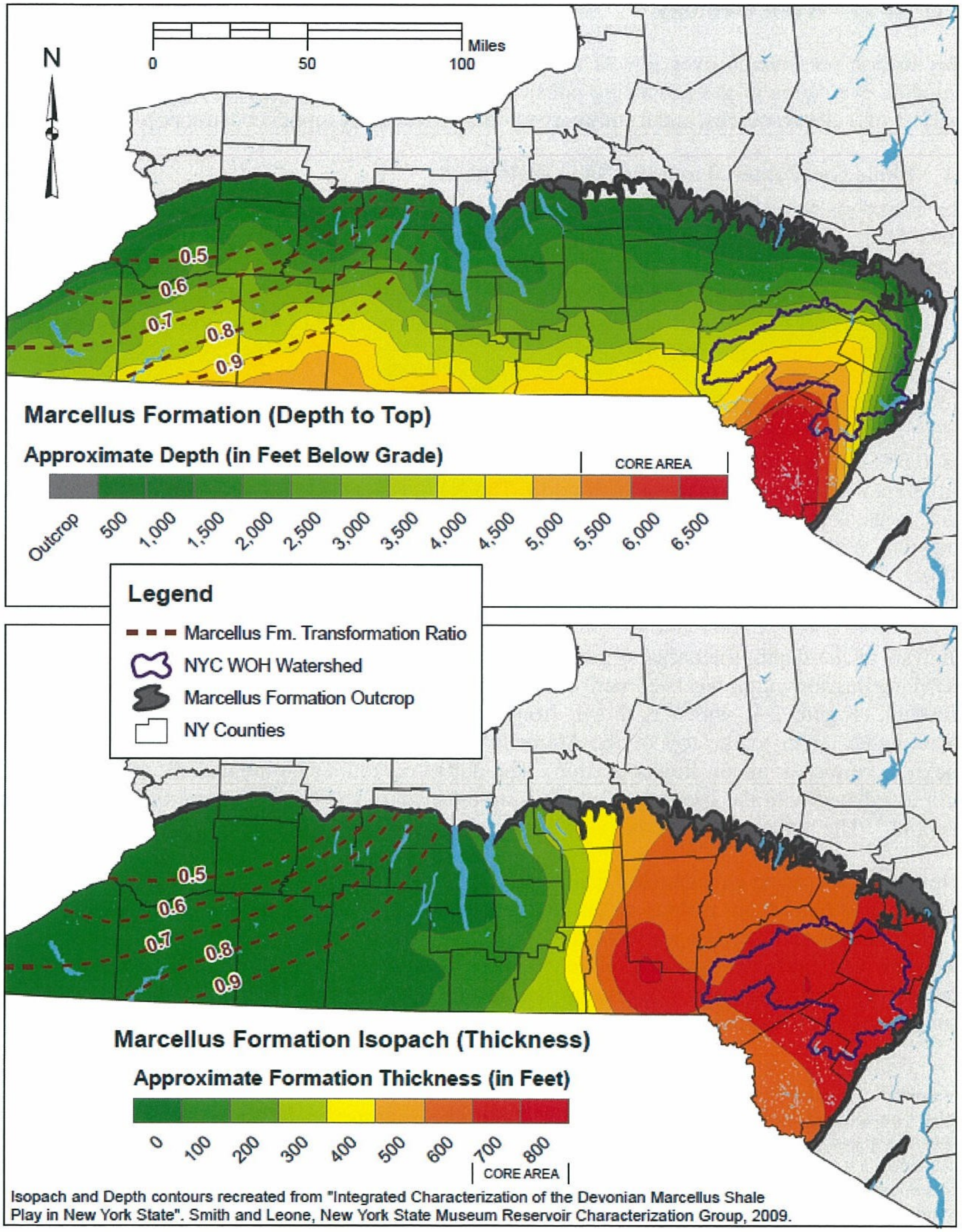

Figure 2-1: Extent and Characteristics of Marcellus Formation in New York

The supposition that the area identified in the New York State Museum study may be highly productive is supported by the intense leasing activity observed in this area and in neighboring counties in northeast Pennsylvania, as well as the ongoing development of a major regional drilling services facility in Horseheads (Chemung County), New York. County locations and additional detail on drilling activity in the region are presented subsequently in Figure 3-4.

2.2 Regional Geology

Figure 2-2 shows the bedrock geology underlying the West-of-Hudson components of NYC's water supply system (Appendix A). It identifies the uppermost layer of underlying bedrock, locations of mapped geologically brittle structures in relation to watershed boundaries, reservoirs, aqueducts, streams and rivers. The contours mapped in Figure 2-2 show the approximate depth to the top of the Marcellus formation. These contours indicate that the formation dips steeply westward in the eastern portion of the watershed, while the dip from north to south is less steep.

The uppermost layer of bedrock is identified in Figure 2-2 by color-coding keyed to the geologic cross-section of Figure 2-3. These figures indicate that virtually the entire watershed is underlain by rock of the West Falls, Sonyea and Genesee Groups, which are Upper (or Late) Devonian period in age (over 360 million years old). The Upper Devonian Groups are in turn underlain by Middle Devonian aged rocks of the Hamilton Group. The orange-shaded band framing the east boundary of the watershed corresponds to Middle Devonian formations and defines the extent of Upper Devonian rock.

The Marcellus formation occurs at the base of the Middle Devonian Hamilton Group and is primarily composed of organic-rich shale units. It is overlain and underlain by sedimentary rock units (e.g., sandstone, shale, siltstone and limestone) of varying natural gas and fossil fuel resource potential. As indicated by Figure 2-3, the Utica Shale, which is part of the Lorraine Group, underlies the Marcellus as well as the entirety of the West-of-Hudson watersheds.

2.3 Water Resources and Hydrogeologic Conditions

The topography of the region comprises six major drainage basins occupied by a NYC reservoir and its tributaries. The three western-most (Cannonsville, Pepacton, and Neversink) are sub-watersheds of the Delaware River Basin; the remaining three (Rondout, Schoharie, and Ashokan) are hydrologically within the Hudson River Basin.

Surface water in the region generally originates as precipitation, which is either captured directly within the waterbody itself, or indirectly, as runoff and groundwater discharge (known as "baseflow"). There is a hydraulically continuous relationship between groundwater and surface water in the region developed from a series of interdependent flow regimes. Under natural conditions, these flow regimes are in hydrogeologic equilibrium as evidenced by major ionic chemical signatures reflective of the comprising water types (i.e., shallow versus deep), indicating that groundwater in very deep geologic formations is typically older and chemically distinct from groundwater in overlying flow regimes.[11] Typically, groundwater from deep formations and flow regimes is not potable, due to high total dissolved solids, and does not mix directly with shallow, fresh groundwater and surface water.

[11] A Conceptual Hydrogeologic Model for the West-of-Hudson watershed region is developed and described in the September 2009 *Rapid Impact Assessment* report.

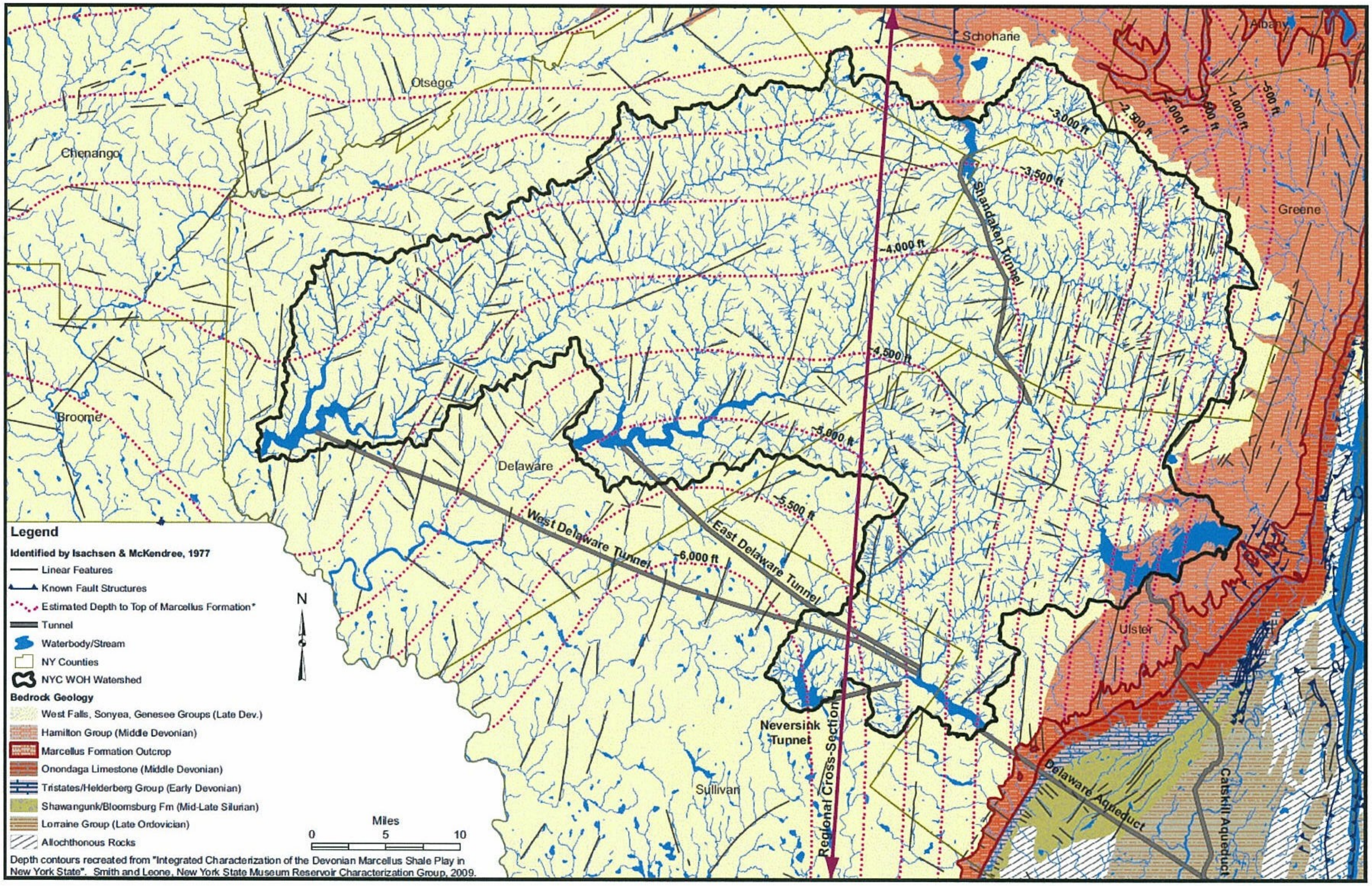

Figure 2-2: Bedrock Geology of the Catskill Region

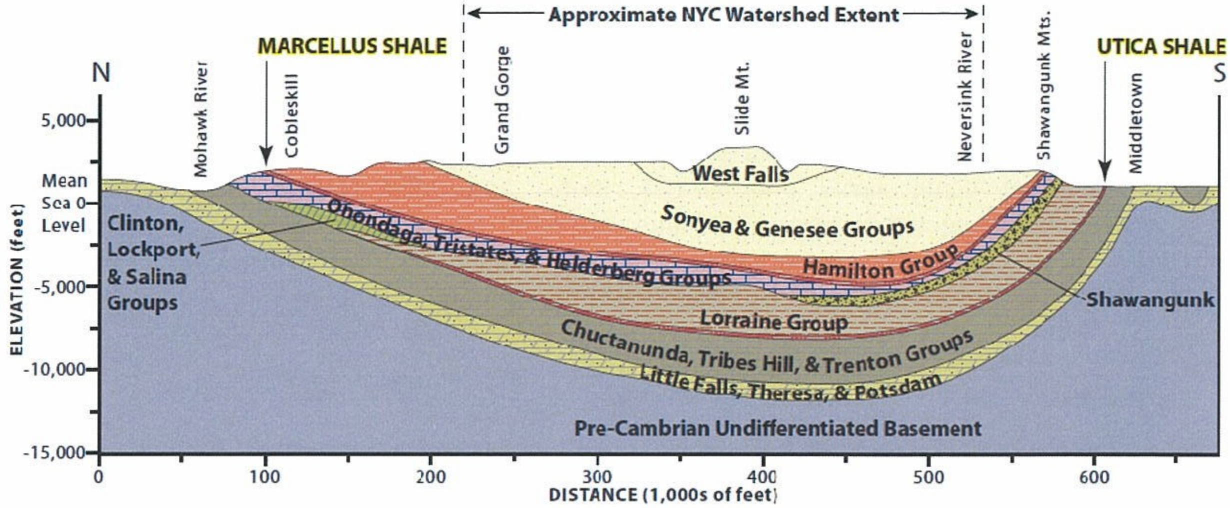

Figure 2-3: Cross-Section of Catskill Region Bedrock Geology

Limited inter-regime flow can be compromised by naturally-occurring, vertically extensive brittle structures as well as the interception of such structures during gas well drilling and stimulation. Abandoned or improperly sealed wells, casing or grouting failures, existing geologic fractures, and new fractures (generated during well development and stimulation) that propagate beyond the target formation can create or enhance hydraulic pathways between previously isolated formations. These hydraulic pathways can permit fluids within geologic formations (such as methane or brine water) to contaminate shallow groundwater, surface water, and subsurface infrastructure. In the case of the Marcellus formation, which is characterized as "overpressurized," fluids in the formation will follow the path of least resistance which, in addition to traveling toward the wellhead, will also follow any existing fractures and be forced upward toward the surface.[12]

2.4 Faults and Other Brittle Structures

The development of natural gas resources using hydraulic fracturing and horizontal well drilling technology relies upon vertical separation distance and low permeability of the intervening rock strata to prevent hydraulic communication between shallow aquifers and deeper gas bearing formations. Given the reliance on overlying rock to isolate hydraulically fractured strata from near-surface flow regimes, an evaluation of the presence and potential extent of geologically formed faults and fractures in the region has been performed. These geological features and other brittle structures can and do serve as conduits that facilitate migration of contaminants, methane, or pressurized fluids from deep formations towards the surface, potentially impacting aquifers and subsurface infrastructure.

Figure 2-4 presents faults, shear zones and other brittle structures as mapped by Isachsen and McKendree (1977) in New York State. The blue-colored features correspond to faults and shear

[12] The dSGEIS (pg. 5-131) reports a pressure gradient in the Marcellus formation of 0.55 to 0.60 psi per foot of depth (i.e., 1.27 to 1.39 feet of pressure per foot of depth). Gas reservoirs that exhibit greater than 0.4 to 0.5 psi per foot of depth (ranging up to 0.7 to 1.0 psi per foot) may be characterized as "overpressurized" (Craft, B.C. and Hawkins, M.F., 1991, *Applied Petroleum Reservoir Engineering*, Prentice Hall).

zones, and the gray features correspond to "Topographic and Tonal Linear Features." Many of these features represent breaks or fractures in the bedrock. The faults and shear zones identified in this study have been mapped on the basis of direct observation in outcrop or boreholes and are associated with movement of the comprising rock masses parallel to the feature. Such movement is commonly associated with "seismic events" such as earthquakes. The "linear features" are typically identified using aerial photographs, maps, and other related methods and may correspond to the suspected locations of faults (although not directly observed in outcrop). In some cases, these features are continuations of known, mapped faults and brittle structures. This data is not likely to present all faults and fractures that might exist at depth

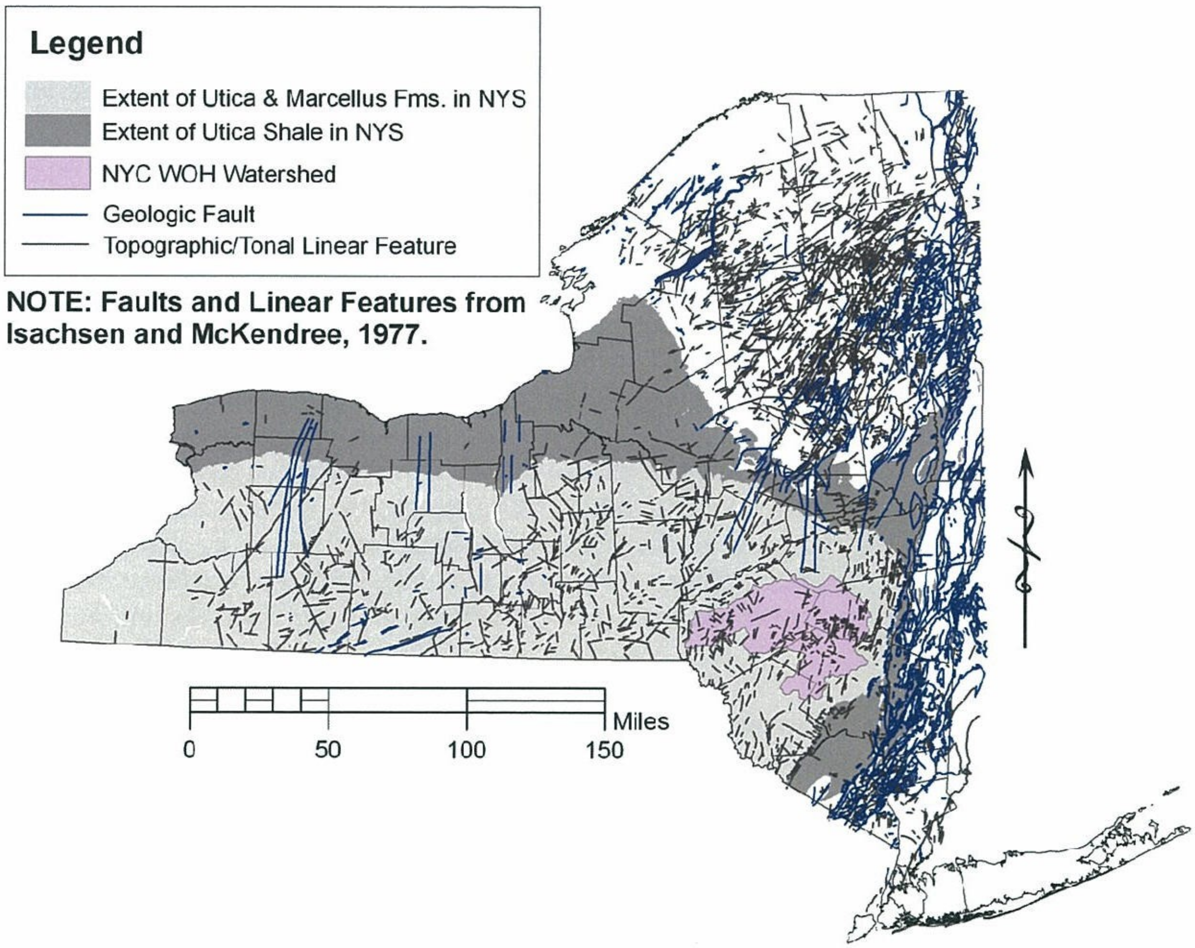

Figure 2-4: Map of Geologic Faults and Linear Features in New York State

Recognizing the significance of brittle structures (i.e., faults, shear zones, fractures and other linear features) to act as migration pathways for fluids from deeper formations, a statistical analysis of the lengths of these reported features in the vicinity of NYC's West-of-Hudson water system has been performed as part of this assessment. The brittle structures in the region commonly extend laterally for distances in excess of several miles and vertically to depths in excess of 6,000 feet. Some of these features intersect one another and some cross NYC infrastructure components. Given that the process relied upon by Isachsen and McKendree to identify the brittle structures concentrated on a large-scale area and recognized only those observable at the land surface, a reasonably conservative assumption is that even more such features and intersections with infrastructure are present. The lengths of identified fractures provide a guide for establishing buffer distances needed to ensure separation of water system components and natural gas drilling activities affecting deep formations.

Based on a statistical analysis of identified fractures and brittle structures in the region, 50 percent of the mapped features have lengths in excess of three miles, and more than 10 percent exceed seven miles in length (Appendix A).

Based on Isachsen and McKendree, the area within and around the NYC watershed is dominated by numerous "linear features" that typically correspond to fractures, both mapped and un-mapped. As such, the intervening rock masses (both horizontally and vertically) between the Marcellus formation and fresh water aquifers or subsurface infrastructure should not be considered as an impermeable barrier, since they are fragmented by a significant number of fractures. The existence of vertical fractures is evident in local rock outcroppings. A local example of such vertically persistent fractures that typify the bedrock character is presented in Figure 2-5, which shows two photos of Plattekill formation outcrops near Ashokan Reservoir. Evident in each photo are vertical fractures that extend across multiple layers of the formation. The Plattekill formation is part of the Hamilton Group of interbedded shales, siltstones and sandstones that overlie the Marcellus formation and underlie NYC tunnels and fresh groundwater and surface water sources.

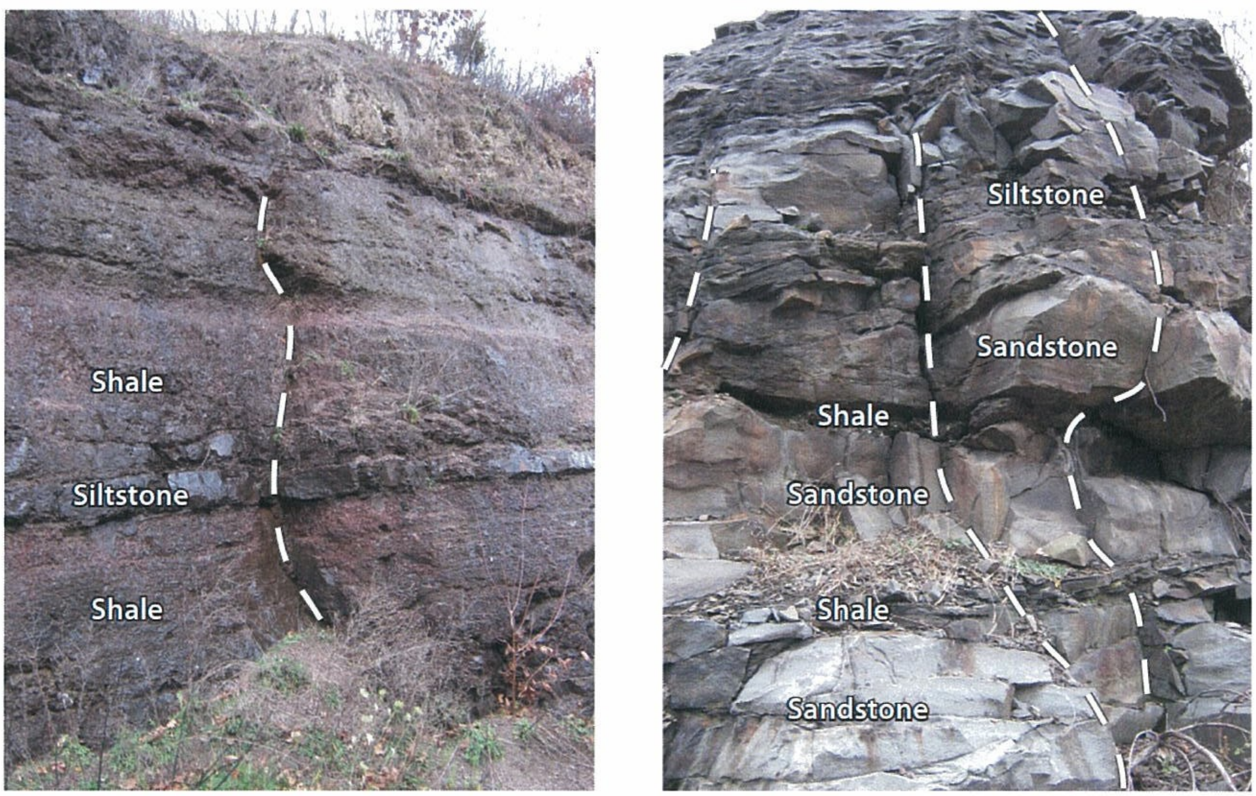

Figure 2-5: Outcrops of the Hamilton Group (Plattekill Formation) near Ashokan Reservoir Showing Persistence of Vertical Fractures across Lithologic Units

2.5 NYC Water Supply Infrastructure Relative to Geological Features

NYC's West-of-Hudson water supply infrastructure has been evaluated in relation to local and regional geologic features. This evaluation has included a review of record drawings and construction documentation, and focused on vertical separation from the Marcellus formation as well as geological features documented during tunnel construction.

Infrastructure Depth and Vertical Separation from Marcellus Formation

The West-of-Hudson water supply tunnels are constructed from several hundred to about 1,000 feet below grade. Regional surface topography ranges from about elevation 1,000 to 2,500 feet. The tunnels upstream of the Rondout and Ashokan Reservoirs are located approximately 1,000 feet above sea level; the tunnels leading from these reservoirs are about 500 feet below sea level. The vertical distance between the Marcellus formation and NYC water supply infrastructure varies from direct contact at the eastern edge of the formation's occurrence, to about 4,500 feet in the western portion of the watershed. Portions of the Shandaken Tunnel, the Catskill Aqueduct, and the bottom of Ashokan Reservoir are separated by as little as 500 feet from the underlying Marcellus formation. Separation increases for infrastructure and reservoirs to the west and the south with increasing depth of the formation. To the west, vertical separation between Delaware system reservoirs and tunnels and the Marcellus ranges from about 2,000 to 4,500 feet.

Geological Features Documented During Construction

Evidence of naturally occurring fluid migration associated with brittle features is reported on record drawings that document the construction of NYC's infrastructure. NYCDEP records indicate that the East and West Delaware Tunnels and Neversink Tunnel construction encountered numerous groundwater seeps, saline water seeps, subsurface fractures, and methane inflows corresponding to the locations of mapped brittle structures. In 1957, methane that had seeped into the West Delaware Tunnel ignited, injuring three miners.[13] Construction of the Rondout-West Branch section of the Delaware Aqueduct also encountered numerous methane seeps. Frequent groundwater and saline water seeps were also encountered during construction of Shandaken Tunnel, sections of the Catskill Aqueduct, and the Rondout-West Branch tunnel.[14] These occurrences substantiate that fractures in the bedrock are naturally providing pathways for the movement of deep formation fluids.

Figure 2-6 highlights a section of the West Delaware Tunnel, where a linear feature identified from regional mapping was encountered as a fault at tunnel depth during construction, as documented in the accompanying excerpt from a tunnel geology drawing. Geological features encountered during construction, including faults and other geological brittle structures, and various seeps, are located on the geologic map of the Delaware system tunnels presented as Figure 2-7. Figure 2-8 shows the geologic features located along a profile of the West Delaware Tunnel, in relation to local surface topography and surficial features, and estimated depth of the Marcellus formation.

[13] The Delaware Water Supply News, April 1, 1964, 23:189, p. 1063.
[14] New York City geologic record drawings.

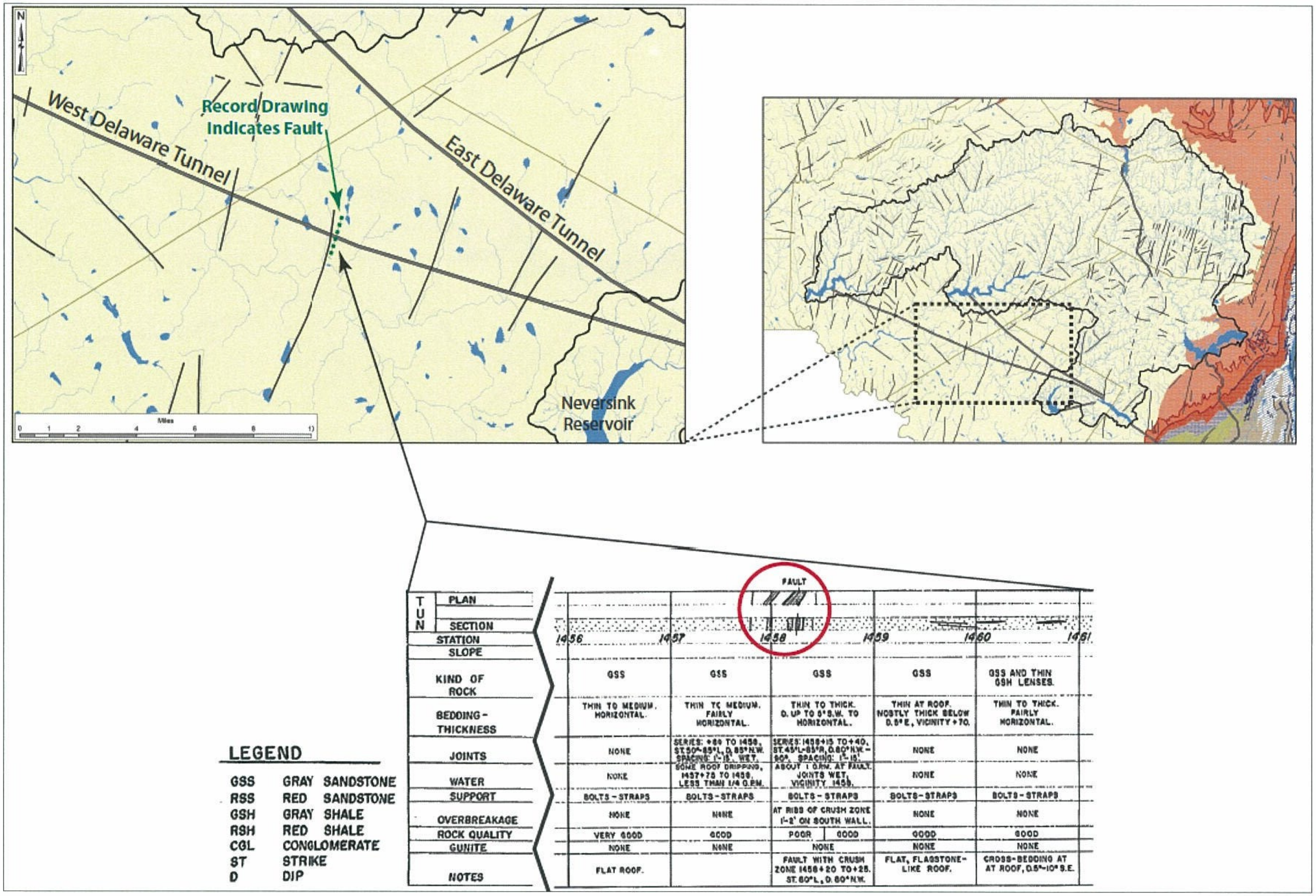

Figure 2-6: Example from West Delaware Tunnel Showing Correlation of Surface Linear Features with Faults Observed During Construction

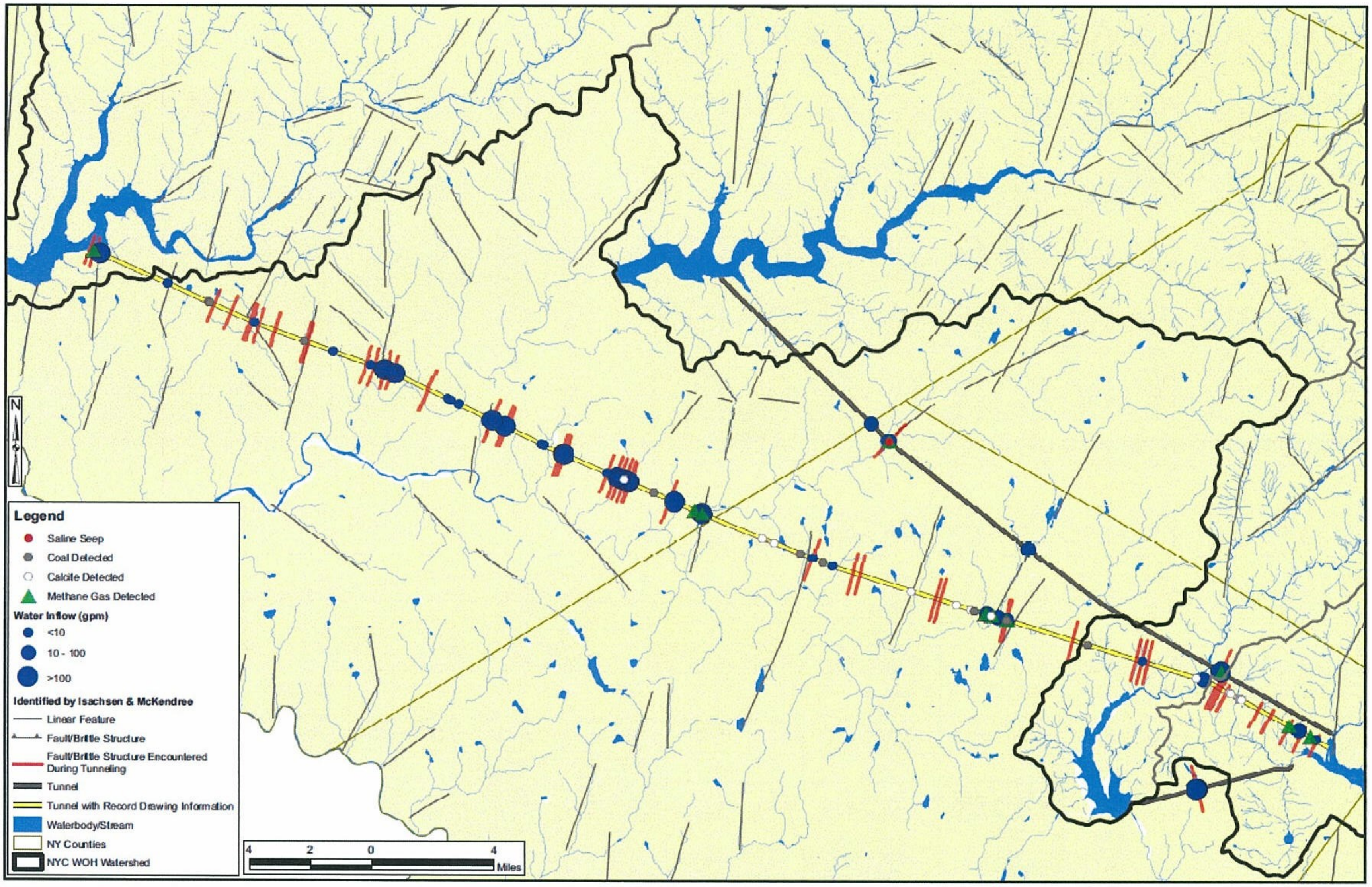

Figure 2-7: Map of the East and West Delaware Tunnels and Neversink Tunnel

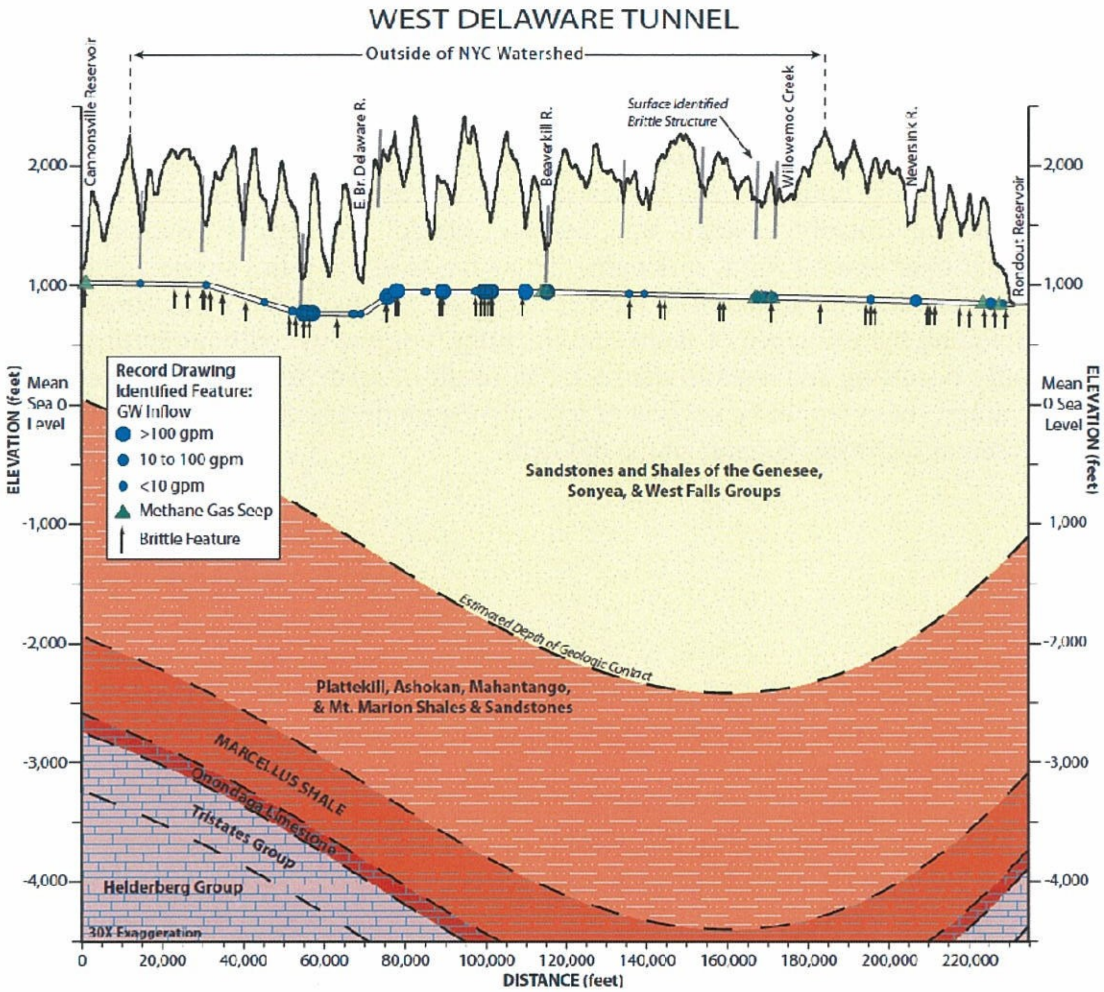

Figure 2-8: Geologic Cross Section of the West Delaware Tunnel

2.6 Summary

Available data, ongoing research performed by the New York State Museum, and comparison with natural gas development progress in northeast Pennsylvania suggests that the NYC watershed is underlain by relatively thick portions of the Marcellus formation with presumably high gas production potential. In addition to the Marcellus, other gas-bearing shale strata underlie the watershed and could be developed in the future. Overall, the NYC watershed area can be expected to be the focus of gas resource development activity comparable to or exceeding that of other contemporary shale gas plays, and this activity can be expected to last for decades.

Under natural conditions, upper geological strata are largely isolated from both methane and water in deep geological strata (formation water). Formation water is typically not potable, even before the addition of chemicals used in the hydrofracturing process. The saline water and methane seeps encountered at grade and in shallow formations near NYC infrastructure during the construction of water system tunnels provide the most reliable evidence that existing fracture systems and pressure gradients will transmit fluid from deeper formations. Taken together with the expected rate and development of gas drilling quantified in Section 3, this evidence of natural migration leads to the conclusion that there is a reasonably foreseeable risk to water supply operations from methane, fracking chemicals, and/or poor quality, saline formation water migrating into overlying groundwater, watershed streams, reservoirs, tunnels, and other infrastructure.

For these reasons, any evaluation of subsurface migration potential associated with future gas development must fully consider all known and foreseeable linear features and fractures. Extensive subsurface fracture systems and known "brittle" geological structures exist that commonly extend over several miles in length, and as far as seven miles in the vicinity of NYC infrastructure (Appendix A). In addition, the net hydraulic conductivity of a formation must be considered, including the influence of faults and fractures, not just the bulk properties of the rock matrix. Naturally occurring fractures in the rock can result in relatively high localized hydraulic conductivity values; these would be several orders of magnitude greater than those considered in analyses provided as technical support of the dSGEIS.