



Technical Memorandum:

**Geophysical Evaluation of
Infrastructure Risks of Natural Gas Production
On New York City
West of Hudson (WOH) Water Supply Infrastructure**

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Section 0: Executive Summary

As interest in development of shale gas resources increased in southern New York, the New York City Department of Environmental Protection (DEP) determined that an objective assessment of potential impacts that natural gas development could have on the City's water supply was needed. Since the shale gas resource targeted for development is located entirely west of the Hudson River, that area was the focus of the assessment. In January 2009, DEP retained a joint venture of Hazen and Sawyer, P.C. and Leggette, Brashears & Graham, Inc. (the JV) to conduct an evaluation focused on the potential impacts of natural gas drilling to water quality, water quantity, and the water supply infrastructure. The results of the JV's studies were used as the basis for DEP's comments on the New York State draft Supplemental Generic Impact Statement (dated September 30, 2009). The JV assessments identified a number of serious risks to the water supply, including but not limited to: chemical contamination of surface and groundwater, risks to the infrastructure, and the industrialization of the watershed. Based on the assessments, DEP concluded that horizontal drilling and high-volume hydraulic fracturing (HVHF) pose an unacceptable threat to the water supply of nine million New Yorkers and are inconsistent with the principles of source water protection and pollution prevention. DEP proposed a complete ban of drilling within the watershed and in a seven-mile buffer around the water supply infrastructure.

In 2011, the New York State Department of Environmental Conservation (NYSDEC) proposed a ban of natural gas drilling using HVHF within the New York City water supply watershed and a 4,000-foot wide zone around the watershed boundary. However, the Revised Draft Supplemental Generic Impact Statement (RDSGEIS) on the Oil, Gas, and Solution Mining Regulatory Program (dated September 7, 2011) issued by the NYSDEC does not contain similar protections for the water supply infrastructure located at the edge of or outside of the watershed boundary (non-watershed infrastructure or NWI). DEP determined that additional analysis focused on the water supply infrastructure located outside the watershed boundary was warranted.

The JV retained Hager-Richter Geoscience, Inc. (Hager-Richter) in October, 2011 to provide expertise from a geophysical perspective on issues relative to the DEP water supply infrastructure raised by the RDSGEIS. The geophysical analysis primarily focuses on potential impacts of horizontal drilling and HVHF activities to the portions of the three DEP water supply tunnels that are located outside the WOH Watershed and in the area of possible HVHF development of shale gas resources in the Marcellus and Utica shales. The geophysical analysis consisted of the following tasks:

- Review existing geophysical data for the vicinity of DEP's water supply tunnels and aqueducts for possible previously unrecognized geologic features of concern such as faults;
- Assess the effects of microseismicity associated with horizontal drilling and HVHF on existing DEP water supply tunnels;

- Evaluate the potential for re-activation of faults as a result of HVHF and the potential risks to DEP water supply tunnels;
- Evaluate the adequacy of the tunnel protections described in the RDSGEIS; and
- Evaluate the 2009 JV recommendations for reducing risks from horizontal drilling and HVHF near NYC water supply tunnels.

Review of Existing Geophysical Data

The geophysical data reviewed included published geophysical maps, reports, and technical papers, and currently available geophysical data for the region, such as orthoimagery, Landsat data, LiDAR data, gravity data, aeromagnetic data, and regional GIS data. Hager-Richter's findings are as follows.

- *The subsurface formations underlying and in the vicinity of the WOH NWI are much more complexly jointed and faulted than indicated in the RDSGEIS, but the joints and faults are not well characterized in the interval between the WOH Watershed Infrastructure and the Marcellus Shale. Figure 4.13 of the RDSGEIS shows "mapped geologic faults in New York State" compiled in 1977, but excludes all linear features (lineaments) that had been judged by the compilers to represent brittle structures in the earth's crust possibly related to bedrock fractures and/or faults. Figure 4.13 shows no fault in either Delaware or Sullivan County where the WOH NWI is located. The RDSGEIS does not consider more recent analyses that indicate much more extensive faulting in the vicinity of the WOH NWI. Examination of existing geophysical data for this project indicates the presence of additional projected faults that cross the WOH NWI. Figure 4.13 of the RDSGEIS does not accurately characterize faulting in the vicinity of the WOH NWI.*
- *Geologic mapping during construction of the 75 miles of the Delaware System tunnels and aqueducts in the 1950's by engineering geologists records numerous faults, crush zones, slickensided joints, shear zones, and brecciated zones. There is good correlation between the locations of faults and related features recorded in the water supply tunnels and surface lineaments detected by others. Faulting documented in the WOH NWI should be considered "known, significant, and mapped," terminology used in the RDSGEIS, because they cross critical infrastructure.*
- *The WOH NWI is in a region of low seismic risk. Seismicity data in the immediate vicinity are limited to three very small events, at least one of which could have been caused by human activity, but they raise the possibility that one or more faults in the vicinity of the WOH NWI is seismically active.*

Assessment of the Effects of Microseismicity Associated with Horizontal Drilling and HVHF on Existing Water Supply Tunnels

- *The vibrations from individual and multiple microseismic events generated due to routine HVHF activities are not likely to damage the tunnels.* This conclusion is based on measured amplitudes of microseisms reported in the literature and on experience of vibration effects gained in the blast and construction vibration discipline.
- Literature review of tunnel failures due to earthquakes shows that tunnels can be damaged by seismic events with magnitudes less than 4 and that tunnels can be damaged by seismic events on faults located greater than 25 km from the tunnel.
- Recently released research has documented that low magnitude earthquakes have been triggered by HVHF treatment of shale gas wells near Blackpool in the UK and possibly in Garvin County, OK. In both cases, the wells were vertical. *The Blackpool site is in a region of low seismicity and the fault was unknown prior to the drilling and HVHF stimulation.*

Evaluation of the Potential for Re-activation of Faults as a Result of HVHF and the Potential Risks to NYC Water Tunnels

- It is documented that thousands of shale gas wells have undergone HVHF treatment in the US without triggering earthquakes, but recently released research has shown that HVHF stimulation of a shale gas well triggered low magnitude earthquakes in the UK and possibly did so in Oklahoma in 2011. *The newly released research demonstrates the possibility that HVHF treatment of horizontal drill holes in the vicinity of the critical WOH NWI could induce one or more earthquakes that the unreinforced concrete lined water supply tunnels would not experience otherwise.*
- Obtaining as much information as possible about the subsurface stress field is critical for engineering HVHF stimulation and in assessing the potential for induced seismicity in any area, but *detailed site specific geophysical data for the WOH NWI region are not available. The absence of direct geophysical data from borehole logging and high resolution seismic reflection surveys, and the natural complexity in rock properties all contribute to the uncertainty in understanding the contemporary stress field and the possible presence of critically stressed faults in the vicinity of the WOH NWI.*
- Modeling an HVHF induced earthquake of the same maximum magnitude of 2.3 recorded for the Blackpool earthquakes indicates a movement of about 3/8 inch on a fault. *At this time, there is not enough known about the state of stress and faulting in the vicinity of the WOH NWI and details about the condition of the unreinforced concrete-lined tunnels of the WOH NWI to determine that the tunnels would not be damaged by an induced seismic event of the type modeled.*
- The Blackpool earthquakes and probably the Oklahoma earthquakes demonstrate that hydraulic fracturing fluids can reach a nearby fault and can trigger a seismic event.

Therefore, *the RDSGEIS statement that “The possibility of fluids injected during hydraulic fracturing the Marcellus or Utica Shales reaching a nearby fault and triggering a seismic event are remote for several reasons” is not consistent with recent evidence of HVHF-induced seismic events.*

- Because the peak horizontal ground accelerations of earthquakes likely to be induced by HVHF are comparable to values determined in a probabilistic seismic hazard analysis of the DEP Catskill/Delaware dams, *we conclude that the potential risk to the dams is no greater than the risk due to natural earthquakes.*

Evaluation from a Geophysical Perspective of the Adequacy of the Tunnel Protections Described in the RDSGEIS

The sole protection in the RDSGEIS is a 1,000-foot buffer zone from the wellhead to the tunnel. Permits can be issued for locations anywhere within 1,000 feet of the NYC WOH Water Supply Tunnels pending a negative declaration of a site-specific SEQRA review.

The protection described above is not adequate to protect the NYC water supply tunnels because:

- Laterals in HVHF directionally-drilled wells may reach as much as a mile horizontally from the well head, so HVHF activities could occur directly under NYC water supply tunnels even if the well head is a few thousand feet outside the 1,000-foot buffer described in the RDSGEIS.
- Faults and brittle structures that cross NYC WOH Water Supply Tunnels have been shown to be more numerous than indicated in the RDSGEIS, and analysis of additional geophysical data could reveal even more faults and brittle structures.
- Recent case studies document that HVHF can induce earthquakes.
- Earthquakes can cause tunnel damage.

Evaluation from a Geophysical Perspective of the 2009 JV Recommendations for Reducing Risks from Horizontal Drilling and HVHF Near NYC Water Supply Tunnels

The 2009 JV recommendations with respect to protecting NYC water supply tunnels and Hager-Richter's responses are as follows:

- Setbacks should be measured from the spacing unit, rather than the wellhead. *Hager-Richter agrees that the minimum setback should be from the edge of the spacing unit so that no lateral will extend under the WOH NWI.*
- Setbacks from tunnels should be seven miles. The JV used a reasonable statistical model for their recommended seven-mile setback.

- Based on the evidence of faulting, the possible reactivation of faulting due to HVHF, and the unprecedented nature of HVHF activity under critical water supply tunnels for a large population, *Hager-Richter agrees with the 2009 JV assessment that a much greater protection than the 1,000-foot buffer afforded in the RDSGEIS is required to protect the WOH NWI.*
- Hager-Richter does not recommend a specific revised setback distance herein because 1) there are too many uncertainties about site specific subsurface geological and geophysical conditions in the vicinity of the WOH NWI, and 2) the condition of the unreinforced concrete-lined water supply tunnels is unknown. The need for extra caution in the vicinity of the WOH NWI is obvious, but what constitutes an acceptable level of risk of damage to the critical water supply infrastructure is more a matter of policy, not geophysics.

Recommendations:

Based on the above findings, Hager-Richter makes the following recommendations:

- *Hager-Richter recommends that horizontal drilling and HVHF treatment not be permitted along a fault mapped in the WOH NWI due to the low, but real possibility of reactivation of a fault that might experience sufficient slippage to damage the unreinforced concrete lining of the critical NYC water supply tunnels.*
- There is not enough geophysical information available to recommend a specific setback distance from the infrastructure along a fault mapped in the infrastructure in which horizontal drilling and HVHF should be barred. If horizontal drilling and HVHF is proposed in the vicinity of one of the faults that cross the water supply tunnels, Hager-Richter recommends that detailed site characterization of the proposed drilling site and the area between that location and the WOH NWI be required to demonstrate that faults are not present and the results provided to NYSDEC and DEP prior to issuing a permit.

Section 1: Introduction

As interest in development of shale gas resources increased in southern New York, the New York City Department of Environmental Protection (DEP) determined that an objective assessment of potential impacts to the City's water supply in the West of Hudson (WOH) Watershed and related infrastructure was needed. In January 2009, DEP retained the joint venture of Hazen and Sawyer, P.C. and Leggette, Brashears & Graham, Inc. (the JV) to conduct an evaluation focused on the potential impacts of natural gas drilling to water quality, water quantity, and the water supply infrastructure. DEP and its consultants, the JV, subsequently issued documents that detail their concerns over protections to the WOH Watershed and water supply infrastructure. These documents include:

- Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed, Rapid Impact Assessment Report, September, 2009 (RIA)
- Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed, Final Impact Assessment Report, December 22, 2009 (FIA)

The RIA and FIA were used as the basis for DEP's comments on the New York State draft Supplemental Generic Impact Statement (dated September 30, 2009). The JV assessments identified a number of serious risks to the water supply, including but not limited to: chemical contamination of surface and groundwater, risks to the infrastructure, and the industrialization of the watershed. DEP concluded that horizontal drilling and high-volume hydraulic fracturing (HVHF) pose an unacceptable threat to the water supply of nine million New Yorkers and are inconsistent with the principles of source water protection and pollution prevention. DEP proposed a complete ban of drilling within the watershed and in a seven-mile buffer around the water supply infrastructure.

In 2011, the New York State Department of Environmental Conservation (NYSDEC) proposed a ban of natural gas drilling using HVHF within the New York City water supply watershed and a 4,000-foot wide zone around the watershed boundary. However, the Revised Draft Supplemental Generic Impact Statement (RDSGEIS) on the Oil, Gas, and Solution Mining Regulatory Program (dated September 7, 2011) issued by NYSDEC does not contain similar protections for the water supply infrastructure located at the edge of or outside of the watershed boundary (non-watershed infrastructure or NWI). DEP determined that additional analysis focused on the water supply infrastructure located outside the watershed boundary was warranted.

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- Review existing geophysical data for the vicinity of DEP's water supply tunnels and aqueducts for possible previously unrecognized geologic features of concern such as faults;

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- Evaluate the adequacy of the tunnel protections described in the RDSGEIS; and
- Evaluate the 2009 JV recommendations for reducing risks from horizontal drilling and HVHF near NYC water supply tunnels.

Each of the tasks is addressed below in the context of the RDSGEIS. The RDSGEIS addresses well permit issuance for horizontal drilling and HVHF in the Marcellus Shale and other low permeability gas reservoirs.

This Technical Memorandum is based in part on existing information available from such sources as documents developed previously by the JV, DEP, the NYSDEC, the United States Geological Survey (USGS), various geological and geophysical journals, and other sources. The objective of this memorandum is to *supplement* information previously presented by the JV regarding potential threats to the DEP water supply infrastructure in and near the WOH Watershed region resulting from horizontal drilling and HVHF. This Technical Memorandum also highlights how geophysical data—such as gravity, geomagnetic, orthoimagery, and LiDAR data—can reveal pre-existing geologic conditions that in conjunction with natural gas development can potentially adversely affect the NYC water system infrastructure.

1.1 Background

This document supplements extensive geologic, water resource, hydrogeologic, and other technical information previously presented by the JV for the areas in the vicinity of the WOH NWI located in areas where horizontal drilling and HVHF may occur.

1.2 Methodology

The following sources of information were used to collect information and data that were reviewed to develop this Technical Memorandum:

- Published geophysical maps, reports, and technical papers
- Currently available geophysical data for the Region, including:
 - Gravity data
 - Aeromagnetic data
 - Orthoimagery
 - LandSat data
 - LiDAR data
- Regional GIS data

Information and data were collected by Hager-Richter from the JV, the DEP, the USGS, the New York State Geological Survey's (NYSGS) GIS Clearinghouse site, the New York State Museum GIS databases, the Empire State Oil and Gas Information System, the NYSDEC, and various geological and geophysical publications. Several data sets use ESRI georeference coordinates, and for those that did not use such coordinates, we added approximate coordinates.

1.3 Short Glossary

Brittle structure is a lineament detected from satellite or other remote sensing imagery and interpreted as a possible bedrock fracture or fault.

Fault is a bedrock fracture along which blocks of rock on either side have moved relative to one another parallel to the fracture.

Fracture is a general term for a break, rupture, or discontinuity in rock due to mechanical failure by stress. The term may be used to describe cracks, joints, and faults.

Horizontal Drilling is drilling where the departure of the wellbore from vertical exceeds about 80 degrees.

High Volume Hydraulic Fracturing (HVHF) is the propagation of new fractures in a rock layer caused by the injection of large volumes (defined in the RDSGEIS as greater than 300,000 gallons) of a pressurized liquid.

Hypocenter is the point within the earth where an earthquake occurs. **Epicenter** is the point on the earth's surface directly above the hypocenter.

Joint is a fracture or parting in rock that does not display displacement parallel to the fracture. Joints are commonly planar.

Jointing is the presence of joints in rock. Jointing commonly occurs in sets of parallel joints with consistent patterns or orientations.

LiDAR (Light Detection and Ranging) illuminates a target with light, commonly using laser pulses, to measure distance and other properties of the target. It provides very high resolution of topography.

Lineament is a linear feature in a landscape, commonly an expression of an underlying geological structure.

Magnitude is a measure of the size of a seismic event, and there are several magnitudes in common use, distinguished by a subscript. The original magnitude was developed by Charles Richter in the 1930s and is currently designated as M_L . It was based on the maximum amplitude of vibration of the

surface. Other magnitudes use surface waves (M_S), body waves (m_b), and seismic moment (M_w). For events of magnitude less than about 5, all magnitudes (except M_S) are approximately equal.^{1,2}

Microseisms, as used in this Technical Memorandum, are seismic events of two types:

- those created by hydraulic fracturing and commonly used to map and monitor in three dimensions the location of fractures created by the process, typically with magnitudes $M_L < -1$; and
- earthquakes of small magnitude caused or triggered by hydraulic fracturing, typically with magnitude $M_L \leq 3$ but $M_L > -1$.

Orthoimagery is an aerial photograph that has been corrected so that the scale is uniform throughout the photograph. The USGS National Map website (www.nationalmap.gov) offers free download of available orthoimagery at 1 m resolution for the conterminous United States.

Seismic moment, M_O , is defined as $M_O = G \cdot A \cdot D$, where G is shear modulus, A is the area of a fault on which displacement D occurs.^{3,4} Using units for G , A , and D of dyn/cm^2 , cm^2 , and cm , respectively, the units for M_O are dyn-cm . The value of G is usually taken as 32 GPa ($3.2\text{E}+24 \text{ dyn/cm}^2$). The Moment Magnitude, M_w , is given^{5,6,7} by $M_w = 2/3 \cdot \text{Log}_{10}(M_O) - 10.7$.

Slickensides are smoothly polished striated surfaces caused by frictional movement between rock on opposite sides of a fault. They commonly show direction of movement.

1.4 Horizontal Drilling and Hydraulic Fracturing

Horizontal drilling and HVHF may interact with the WOH NWI through fractures, faults, and induced seismicity, and the analysis of those geologic features using geophysical techniques is discussed in the other sections of this Technical Memorandum. The combination of horizontal drilling and HVHF is required for commercial success in exploiting shale gas in general and the Marcellus Shale gas in particular. In this Introduction section, we provide brief descriptions of each and references for more extensive descriptions.

¹ Day, 2002

² Elnashai and Di Sarno, 2008

³ Day, 2002

⁴ Elnashai and Di Sarno, 2008

⁵ Kanamori, 1977

⁶ Hanks and Kanamori, 1979

⁷ Day, 2002

1.4.1 Horizontal Drilling

Horizontal drilling is the technology used to drill horizontal boreholes. Briefly, the borehole begins as a vertical borehole and gradually changes to a horizontal borehole using a change of perhaps about 5° to 10° per 100 ft in the build section (the section of the borehole between the vertical and horizontal sections). The technology uses logging while drilling (LWD), steerable downhole drill motors or rotary steerable systems that have achieved builds at 10°/100 ft to as much as 17°/100 ft, mud pulse or EM telemetry to transmit downhole data to the surface for monitoring and control, and drill bits designed specifically for use in shale.⁸

Typically, several wells will be drilled in different directions from a single location, a well site or well pad. The horizontal portions of the boreholes, called laterals, can be as long as 5,000 ft.

There were apparently 51 horizontal wells worldwide in 1987, but 10 years later the number had increased to almost 5,000. By the end of 2001, there were 34,777 horizontal wells in 72 countries, with more than 5,400 in North America alone. These statistics, from Stark 2003,⁹ together with the review by Greenberg¹⁰ of drilling in the Marcellus Shale, demonstrate clearly that by 2011 the technology of horizontal drilling has matured.

1.4.2 High Volume Hydraulic Fracturing (HVHF)

HVHF is a formation stimulation process in which new fractures are created and existing fractures are enhanced in a target formation to increase permeability. As noted above, HVHF is critical to the commercial success in exploiting tight (extremely low permeability) gas formations such as the Barnett Shale of Texas and Oklahoma and the Marcellus Shale and Utica Shale of Pennsylvania and New York.

In HVHF, very large volumes of water that include chemicals for various purposes and proppants (commonly sand grains) to help keep fractures open are pumped into the formation at pressures sufficient to overcome the minimum in situ stress (stress is a tensor and varies in direction) plus the tensile strength of the formation rock. The volume is commonly several millions of gallons. Arthur, et al.¹¹ provide an excellent review of HVHF with respect to the Marcellus Shale play. Typically, only 10% to 30% of the water used for fracturing returns to the surface.¹²

The bottom hole pressures are monitored in order to control the production of the fractures. However, such monitoring alone does not provide information on where the fractures are being produced. The location of the fractures can be monitored in real time for improved control of the fractures and, especially, of their location. Such monitoring uses seismological methods to locate the

⁸ Greenberg, 2011

⁹ Stark, 2003

¹⁰ Greenberg, 2011

¹¹ Arthur, et al., 2008

¹² Rassenfuss, 2011

microseisms produced when fracturing occurs, and requires sensors in nearby boreholes and/or many sensors on the surface.^{13,14,15} HVHF technology is apparently still advancing, and microseismic monitoring is becoming more widely used in the industry.

1.5 DEP Water Supply Infrastructure Outside the WOH Watershed

The three DEP Delaware System Water Supply Tunnels partially located outside the WOH Watershed and in areas of possible HVHF development of the Marcellus Shale and Utica Shale are the West Delaware Tunnel, the East Delaware Tunnel, and the Neversink Tunnel. Those three water supply tunnels were constructed in the 1950's and constitute critical facilities for transporting water to nine million people in the New York City area. They are the primary focus for the geophysical evaluation in this Technical Memorandum.

The West Delaware Tunnel transports water from the Cannonsville Reservoir in western Delaware County to the Rondout Reservoir at the eastern edge of Sullivan County. The West Delaware Tunnel is 44 miles long, of which about 36 miles are located outside the WOH Watershed. The tunnel elevation varies between about 1150 and 840 feet above sea level. The West Delaware Tunnel is located between about 300 and 1350 feet below the ground surface.

The East Delaware Tunnel transports water from the Pepacton Reservoir to the Rondout Reservoir. The East Delaware Tunnel is about 26 miles long, of which about 14 miles are located outside the WOH Watershed. The tunnel elevation varies between about 1140 and 840 feet above sea level. The East Delaware Tunnel is located between about 500 and 1700 feet below the ground surface.

The Neversink Tunnel transports water from the Neversink Reservoir to the Rondout Reservoir. The Neversink Tunnel is about five miles long, of which three miles are located outside the WOH Watershed. The tunnel elevation varies between about 1300 and 900 feet above sea level. The Neversink Tunnel is located between about 240 and 1300 feet below the ground surface.

All three DEP Delaware System water supply tunnels are circular in cross-section and are lined with 10" of unreinforced concrete. The West and East Delaware Tunnels are 11' 4" in diameter, and the main length of the Neversink Tunnel is 10' in diameter.

¹³ Duncan and Eisner, 2010

¹⁴ Duncan and Williams-Stroud, 2009

¹⁵ Eisner, et al., 2010

Recent tunnel inspections have not been made, and current conditions of the unreinforced concrete linings are not known. A structural analysis of the Delaware System tunnels by Jenny Engineering Corp¹⁶ notes that the “unreinforced concrete linings of the DEP water supply tunnels and aqueducts are structurally sensitive to the effects of external pressures in excess of those that they presently experience. The linings could experience detrimental effects under much lower pressures than are proposed for fracturing the bedrock.”

¹⁶ Jenny Engineering Corporation, 2009

Section 2: Existing Geophysical Data

2.1 Introduction

Existing geophysical data have been reviewed by Hager-Richter to detect geologic features of concern such as faults and fractures between the Marcellus Shale and the surface and to assess the potential impacts of such features on the WOH NWI.

The geophysical data types included in this analysis are joints and faults mapped or described in geologic literature, lineaments interpreted by others from Landsat and other imagery, orthoimagery, LiDAR, seismicity, gravity, and aeromagnetic. Some of the existing data (orthoimagery and LiDAR) were acquired for investigations of the WOH Watershed and associated infrastructure by the DEP, and some were acquired for other purposes.

Figure 1 is a combined data plot for the WOH NWI located outside the Watershed boundaries that shows on a GIS base plot the locations of:

- The WOH Watershed boundary;
- The WOH Watershed tunnels and 1,000-foot buffer as specified in RDSGEIS;
- Orthophoto images of the tunnel alignments and adjacent portions of the WOH Watershed;
- Brittle structures of Isachsen and McKendree¹⁷;
- Fractures of EarthSat¹⁸;
- Proposed faults of Jacobi¹⁹;
- Geologic features such as faults and joint zones mapped during tunnel construction; and
- Additional features discussed in the sections below.

LiDAR data for the WOH Watershed were examined but are not plotted in Figure 1 because the data coverage does not extend into areas outside the watershed, and the data would obscure the high resolution orthophoto images where LiDAR data are available.

¹⁷ Isachsen and McKendree, 1977

¹⁸ EarthSat, 1997

¹⁹ Jacobi, 2002

2.2 Joints, Faults, and Lineaments Near the WOH Non-Watershed Infrastructure

Regional joint systems and faulting have been documented extensively in the Marcellus Shale and overlying Devonian bedrock units in the region of the Marcellus gas play. In this section, we focus on the joints, faults and lineaments in the vicinity of the WOH NWI located outside the watershed boundaries.

2.2.1 Joints

Chapter 4 of the RDSGEIS on Geology does not specifically describe the joint systems and structural geology of the Marcellus Shale and the sequence of overlying sedimentary formations that form the fracture barrier between the zones of HVHF and the surface. Joints are systematic sets of natural fractures that are structural discontinuities in bedrock that show no evidence of movement. Regional planar jointing with consistent patterns has been characterized and extensively researched and documented in the Marcellus Shale and related stratigraphic units in Pennsylvania and New York (only a few of the many references are cited here).^{20, 21, 22, 23, 24} In particular, the two pervasive joint sets in the Marcellus, commonly designated as J1 and J2, are considered critical to understanding the tectonic setting for the Marcellus Shale and for optimizing natural gas extraction by hydraulic fracturing of horizontally drilled boreholes.^{25, 26, 27, 28}

The J1 joints are the older set of joints and are generally oriented ENE. The J1 joints are also oriented essentially parallel to the current direction of maximum horizontal stress (S_H). The J2 joints are oriented NNW, essentially parallel to the direction of least horizontal normal stress. Engelder et al.²⁹ interpret both joint sets as natural hydraulic fractures induced by fluid pressures during thermal maturation of the shale at maximum burial depth millions of years ago, and note that the J1 set is more closely spaced than the J2 set. Since the J1 set happens to be nearly parallel to the maximum compressive normal stress of the contemporary stress field, Engelder et al. recommend that horizontal drilling for HVHF be oriented NNW to cross and drain gas from the J1 set. They further note that staged hydraulic fracturing along NNW horizontal laterals will open additional fractures ENE parallel to the J1 set, thereby crosscutting and draining gas from the J2 sets. Much of the HVHF activity in the Marcellus in recent years in Pennsylvania has followed the recommended drilling pattern with success and most 640-acre rectangular spacing units for HVHF horizontal drilling sites are oriented NNW.^{30, 31}

²⁰ Engelder and Geiser, 1980

²¹ Geiser and Engelder, 1983

²² Lash et. al., 2004

²³ Engelder and Whitaker, 2006

²⁴ Engelder, 2008

²⁵ Lash and Engelder, 2009

²⁶ Engelder et. al., 2009

²⁷ Durham, 2011

²⁸ Engelder, 2008

²⁹ Engelder et. al., 2009

³⁰ Zagorski, 2010

The J1 joints are primarily present in the Marcellus Shale, but Engelder has recently described the J2 joints as extending for some distance into the formations above the Marcellus.^{32, 33} In an October, 2011 AAPG Explorer article by Durham,³⁴ Engelder is quoted as follows:

“The J2 set appears to break out of the gas shales and populate the rock above those gas shales. This second joint set may appear about 1,000 feet or even as much as 4,000 feet above the gas shale.

“We interpret this to mean that a large enough volume of gas was generated so the section above the gas shale became over-pressured to the extent it also was [naturally] hydraulically fractured. So the section above the gas shale became charged with high-pressure gas as well.

“There appears to be a strong correlation between fracturing above the gas shales by HVHF and the productivity of the source rock. The correlation indicates a gas column above the gas shale that could have extended maybe 3,000 to 4,000 feet above the Marcellus – although it’s usually not that much. This is what we call the gas halo.

“Of course, much of the gas in the halo has bled back to hydrostatic during exhumation, leaving only the Marcellus over-pressured.

“One measure of productivity, then, of a gas shale may well be the extent to which fracturing occurs – not only in the gas shale itself, but in the halo or gas plume that occurs over the top of the gas shale.”

Hydraulic fractures created as part of HVHF shale gas stimulation are engineered to develop in the target formation and should not grow into formations above or below the target zone. Natural fracture barriers help constrain the height of induced fractures. Limestones and shales of the Mahantango Formation are considered to be the fracture barrier over the Marcellus in the eastern part of New York State,³⁵ but few data are available to assess the variability of jointing and fracturing of those units in the region of the WOH NWI.

Joint mapping by Geiser and Engelder³⁶ indicates the widespread presence of joints in Delaware and Sullivan Counties with orientations similar to or somewhat more easterly than the J2 jointing, which may indicate that J2 jointing is widely present in the sedimentary units above the Marcellus Shale near the WOH NWI. Whether the jointing mapped by Geiser and Engelder in Delaware and Sullivan Counties is due to a naturally hydraulically fractured ‘gas halo,’ i.e., that was charged with

³¹ Bruner and Smosna, 2011

³² Engelder, 2008

³³ Engelder, 2011

³⁴ Durham, 2011

³⁵ Engelder, 2008

³⁶ Geiser and Engelder, 1983

high-pressure gas from the Marcellus Shale located approximately 3,000 to 4,000 feet below the WOH NWI, cannot be shown at this time due to lack of available geophysical well logs and high resolution seismic data for the vicinity of the WOH NWI.

2.2.2 Faults and Lineaments

Figure 4.13 of the RDSGEIS purports to show “mapped geologic faults in New York State” compiled by Isachsen and McKendree³⁷ but notes that certain features on the Isachsen and McKendree maps “identified as drillholes, topographic, and tonal linear features were excluded.” Figure 4.13 of the RDSGEIS does not show any “mapped” fault in either Delaware or Sullivan County where the WOH NWI is located.

The faults and shear zones mapped by Isachsen and McKendree were identified on the basis of direct observation in outcrop or in borehole logs and cores, and the linear features were identified on the basis of aerial photographs, satellite imagery, and maps. As noted by Alpha,³⁸ the Isachsen and McKendree maps “are designated as ‘preliminary’ in nature for purposes that include ‘aid in the selection of exploration targets for oil, natural gas, and economic mineral deposits’ and to ‘identify major fracture conduits for ground water recharge and circulation.’”

The portion of the Isachsen and McKendree maps included in Figure 4.13 of the RDSGEIS excludes all linear features, also known as lineaments, that had been judged by Isachsen and McKendree to represent brittle structures in the earth’s crust possibly related to bedrock fractures and/or faults. Alpha appears to rely on a statement made by Engelder during an oral presentation in 2010 that the use of lineaments to map crustal faults is highly controversial because few faults are mapped at the surface,³⁹ yet lineament mapping and remote sensing are routinely used in the private and public sector, including the USGS, for purposes that include detection of possible faults.^{40,41,42,43,44,45,46,47,48} Geological professionals with extensive field mapping experience such as Isachsen and McKendree are more likely to select brittle fracture lineaments that could be related to faults than inexperienced individuals.

The USGS Earthquakes Hazards website glossary defines lineament as:

³⁷ Isachsen and McKendree, 1977

³⁸ Alpha Geoscience, 2011

³⁹ Engelder, 2010

⁴⁰ Sabin, 1978

⁴¹ Lillesand and Kiefer, 1994

⁴² Gupta, 2010

⁴³ Hill, et al., 2002

⁴⁴ Everett, et al., 2003

⁴⁵ Crone and Wheeler, 2000

⁴⁶ Alexander, et al., 2005

⁴⁷ Reddy and Kappel, 2010

⁴⁸ Williams, 2011

“A linear topographic feature, or an alignment of topographic features or other surficial features that may reflect control by the underlying geology. Some lineaments are defined by alignments of vegetation, patterns in drainage systems, subtle color changes visible on aerial photographs, or cultural features such as fence lines or power lines. Some lineaments are associated with faults.”

The locations of linear features in the vicinity of the WOH NWI mapped as brittle structures by Isachsen and McKendree are shown on Figure 1 as downloaded from the GIS data set labeled “NY Faults” on the New York State Museum website.⁴⁹ Although all topographic lineaments recognized by remote sensing methods are not necessarily due to faults, the JV’s 2009 FIA documents that several of the linear features mapped by Isachsen and McKendree, but excluded from Figure 4.13 of the RDSGEIS, cross the WOH NWI tunnels at locations of faults mapped in the tunnels during construction. Such correlation could reasonably be interpreted as demonstrating that such lineaments are indeed faults that extend to at least the tunnel depth and possibly much deeper.

Chapter 4 of the RDSGEIS also does not consider or discuss more recent state-wide remote sensing and fracture analysis conducted by Earth Satellite Corporation (EarthSat) for NYSERDA and published in 1997.⁵⁰ The objective of the EarthSat project was “to provide a data set that will assist in the evaluation of, exploration for, and exploitation of fractured rock reservoirs in the state of New York.” The EarthSat study focused on the organic-rich black and brown shales of Ordovician and Devonian age, which include the Utica Shale (Ordovician) and Marcellus Shale (Devonian). According to its report, EarthSat reviewed data on known faults and structures in the region, the distribution, thickness, depth of burial, and total organic content of the target shale units, basin location, tectonic deformation, and maturation history of the shales, oil and gas field production statistics, and geophysical data such as well logs, and gravity and magnetic anomaly maps as well as Landsat satellite imagery. The EarthSat report does not mention or cite the Isachsen and McKendree maps, implying that the EarthSat interpretation was made independently of the Isachsen and McKendree results. The locations of linear features in the vicinity of the WOH NWI mapped by EarthSat are shown on Figure 1 as downloaded from the GIS data set on the Empire State Oil and Gas Information website.⁵¹

Chapter 4 of the RDSGEIS also does not consider further analysis of the EarthSat data by Jacobi published in 2002.⁵² Jacobi correlated fracture intensification domains (FIDs) and faults in outcrop in several locations across New York State with lineaments mapped by EarthSat. He observed that FIDs follow faults and not the J1 and J2 regional joint sets discussed in Section 2.2.1 of this Technical Memorandum. Jacobi proposed additional faults and extended previously mapped faults based on the EarthSat lineament maps, gravity and magnetic data, and he observed a spatial relationship between recorded seismic events and the proposed faults.

⁴⁹ <http://www.nysm.nysed.gov/gis/#faults>

⁵⁰ EarthSat, 1997

⁵¹ <http://esogis.nysm.nysed.gov/nyserdaDownloadPage.cfm>

⁵² Jacobi, 2002

Jacobi suggests that two small seismic events recorded in eastern Delaware County could be related to 1) a southern extension of the N-S Sprakers Fault, mapped to the north in Schoharie and Montgomery Counties, 2) faults related to a geophysical feature known as the Scranton Gravity High, or 3) the intersection of those trends. Jacobi also extends the N-S Noses Fault, mapped to the north in Schoharie and Montgomery Counties, into eastern Delaware County and western Ulster County. Both the Sprakers Fault and Noses Fault are shown on Figure 4.13 of the RDSGEIS. Jacobi's proposed extension of the Sprakers Fault crosses the location of the WOH NWI, and his interpreted extension of the Noses Fault nearly does. Their approximate locations near the WOH NWI are shown on Figure 1.

Jacobi states that almost all of the seismic events in the Appalachian Basin portion of New York State can be correlated with known and suspected faults, and that it appears that more faults in New York State are seismically active than previously thought. He also notes that "these seismically active faults crisscross a large portion of NYS. The high number of faults means that most cultural facilities (e.g., waste disposal sites, bridges, and pipelines) are not far from a seismically active fault."

Jacobi and colleagues have continued their studies and published widely on the topic of faults in New York State and their significance, incorporating additional data from field observations, soil gas studies, proprietary 2D and 3D seismic reflection data, proprietary geophysical well logs, and other sources (only a few of the many references are cited here).^{53, 54, 55, 56, 57, 58, 59}

Isachsen and McKendree, EarthSat, and Jacobi evidently did not include faults mapped during construction of the West Delaware, East Delaware, and Neversink Tunnels⁶⁰ in their state-wide compilations, which is understandable given the broad regional scope of their projects and the difficulty in accessing the historic tunnel mapping data. Geraghty and Isachsen⁶¹ later compared faulting mapped in the water supply tunnels of the entire Delaware Aqueduct system with surface geology as displayed on the 1971 State Geologic Map of New York⁶² and the 1977 Preliminary Brittle Structures Map of New York.⁶³ They found poor correlation between the faults and crush zones mapped in the West Delaware and East Delaware Tunnels and surface geology shown on the 1971 State Geologic Map of New York, but they noted that five faults, crush zones, or jointed zones do correspond to photolinear features noted on the 1977 Isachsen and McKendree Preliminary Brittle Structures Map of New York.

⁵³ Jacobi and Fountain, 2002

⁵⁴ Jacobi, 2010

⁵⁵ Stroup, et al., 2006

⁵⁶ Jacobi, et al., 2011a

⁵⁷ Smith et al., 2011

⁵⁸ Jacobi, et al., 2011b

⁵⁹ Jacobi, 2011

⁶⁰ Fluhr, 1957 and New York City Geologic Record Drawings

⁶¹ Geraghty and Isachsen, 1979

⁶² Fisher, et al., 1971

⁶³ Isachsen and McKendree, 1977

The three DEP Delaware System water supply tunnels essentially constitute 75 miles of uninterrupted, horizontal oriented bedrock section located several hundred to more than a thousand feet below the surface. The geologic information recorded by engineering geologists during tunnel construction in the 1950's provides a rare and unique window of opportunity to assess directly observed faulting in bedrock in the vicinity of the West Delaware, East Delaware, and Neversink Tunnels. There should be no question about the identification of those faults. Relatively detailed geologic record drawings are available for only the West Delaware Tunnel.⁶⁴ Fluhr and Terenzio⁶⁵ provide general profiles and summarize mapping of faults and fracture zones encountered during construction of the East Delaware and Neversink Tunnels as well as other infrastructure of the New York City water supply system. The geologic records indicate that numerous faults, crush zones, slickensided joints, shear zones, and brecciated zones were crossed during construction of the 44-mile long West Delaware Tunnel. Several faults and fracture zones were crossed by the 26-mile long East Delaware Tunnel, and one significant fault was crossed near Wynkoop Brook in the five mile length of the Neversink Tunnel.

The locations of faults and related structural features mapped and documented during construction of the WOH NWI are shown on Figure 1. As noted previously in the JV 2009 FIA and by Geraghty and Isachsen above, there is good correlation between the locations of mapped faults in the West Delaware Tunnel and the locations of lineaments detected by Isachsen and McKendree.⁶⁶ The correlation is even better with the addition of the EarthSat data⁶⁷ and the approximate locations of the proposed faults of Jacobi.⁶⁸ Figure 1 also shows the locations of projected previously unmapped possible faults detected on the basis of lineament bundles mapped by Isachsen and McKendree and EarthSat, the NYCDEP high resolution orthoimagery along the WOH NWI, LiDAR data within the WOH Watershed, and the faults mapped during construction of the West Delaware, East Delaware, and Neversink Tunnels. One of the projected possible faults extends Jacobi's proposed extension of the Noses Fault through faults mapped in the East Delaware and West Delaware Tunnels and the one fault mapped in the Neversink Tunnel. *We conclude that it is reasonable to consider the directly observed tunnel faults that correlate with lineaments as "mapped faults," and that Figure 4.13 in the RDSGEIS is not sufficient to characterize mapped faulting present in the vicinity of the WOH NWI.*

⁶⁴ New York City Geologic Record Drawings

⁶⁵ Fluhr and Terenzio, 1984

⁶⁶ Isachsen and McKendree, 1977

⁶⁷ EarthSat, 1997

⁶⁸ Jacobi, 2002

2.3 Seismic Reflection Data and Geologic Features Between the WOH Non-Watershed Infrastructure and the Marcellus Shale

Do the faults mapped in the vicinity of the WOH NWI extend through the so-called fracture barrier formations to the depths of the Marcellus Shale? There is no geophysical evidence to suggest that they do not.

The oil and gas industry has used seismic reflection data to investigate the subsurface not only for the presence of geologic conditions suitable for oil and gas accumulations but also for faults, fractures, and other structures. Very few exploratory wells have been drilled in the past 60-70 years without supporting seismic information. In addition, many seismic data sets have been acquired for reconnaissance.

The oil and gas industry operated in New York State for many years before the Marcellus play became active. The NYSDEC website states:

“Oil, gas and solution salt mining wells are economically important in New York State with more than 75,000 wells drilled in the state since the late 1800's; about 14,000 of these are still active and new drilling continues. Extraction of oil and gas contributes half a billion dollars to the state's economy each year. Wells are also drilled in New York for underground gas storage, geothermal heating/cooling, stratigraphic exploration and brine disposal.”

NYSDEC's 2010 Oil and Gas Production Data website states:

“For the 2010 calendar year, total reported gas production was 35.802 billion cubic feet (bcf), a 20% decrease from 2009's posted production of 44.849 (bcf). As in recent years, the 2010 production was primarily driven by wells in the Trenton-Black River formation. However, steady production from the Medina, Herkimer, and Queenston formations, continues the return to more traditional gas sources in New York State.

“Oil production in New York increased 16% from the previous year for a total of 387,349 barrels reported by purchasers. 772 Well owners also reported a total of 13,534 oil and gas wells. In response to the Department's e-commerce initiatives, owners electronically reported 56 percent of wells and 89 percent of gas production.”

On the basis of information contained in NYSDEC's websites, it appears that considerable seismic data have been acquired. Of course, not all of it is useful for assessing potential impacts on the DEP water supply tunnels due to Marcellus Shale exploration/development activities, and some data that might be useful are not available. The value of even vintage 2D seismic data for determining the presence of faults and fractures in the Marcellus Shale play was recently emphasized by a direct quote in the AAPG Explorer from an oral presentation by James Morris, Chief Geophysicist for

Range Resources Corp's Marcellus Shale division in Pittsburgh at the AAPG 16th Annual Seismic Symposium in 2010⁶⁹ as follows:

“Vintage 2-D will allow you to map a regional structure and identify major faults, ‘Morris told the 700 attendees.’ Newer 2-D can help identify even smaller structural features and faults.”

The geophysical methods available to determine the persistence of faulting with depth are high resolution 2D and 3D seismic reflection surveys and geophysical well logs of the types routinely obtained by oil and gas firms prior to extensive drilling and development of a resource such the Marcellus Shale.^{70,71} Such high resolution seismic and geophysical well log data are not available in the public domain for the vicinity of the WOH NWI.

Norse Energy Corp. USA has recently offered its Marcellus and Utica Shale assets in neighboring and nearby Broome, Chenango, and Madison Counties, New York for sale.⁷² The prospectus for the sale includes as part of the offer 408 miles of proprietary 2-D and 76 square miles of proprietary 3-D seismic data, which is an indication of the level of effort made in characterizing the subsurface prior to HVHF horizontal drilling. Those proprietary seismic data could be used to document whether similar faulting is present or absent in the fracture barrier formations between the Marcellus Shale and the depths of the WOH NWI, but they are obviously not available for review.

Recent publications and presentations by Jacobi and colleagues indicate that extensive proprietary geophysical data have been examined for locations in New York State outside the WOH Watershed, and the authors do not seem to indicate that the proprietary geophysical data contradict their interpretation that extensive faulting is present in the Marcellus Shale Fairway. For example, the abstract for an oral presentation at the Hudson-Mohawk Professional Geologists' Association on November 16, 2011 by Jacobi, who was recently Director of Special Projects for Norse Energy, states that the Appalachian Basin

“is riddled by literally thousands of faults. These faults have partly controlled the deposition of the sedimentary units, including black shales. Some of the faults are seismically active. . . This presentation shows how we first recognized these fault systems, and then examines the Mohawk Valley fault system – including a subsurface view of the faults in seismic reflection data.”⁷³

Jacobi may have had access to some of the seismic data mentioned in the paragraph above.

⁶⁹ AAPG Explorer July 2010

⁷⁰ Morris, 2009

⁷¹ Yang and Morris, 2011

⁷² <http://www.albrechtai.com/oil-gas-divestitures.html>

⁷³ Jacobi, 2011

2.4 Seismicity Near the WOH Non-Watershed Infrastructure

Recorded seismicity in the immediate vicinity of the WOH NWI is very low. The region of the WOH NWI is located in an area of low seismic risk on the New York State Seismic Hazard Map (Figure 4.14 of the RDSGEIS). Figure 4.15 of the RDSGEIS is a plot of seismic events recorded in New York State between 1970 and 2009 by the Lamont-Doherty Cooperative Seismic Network (LCSN). Three small events were recorded in Delaware County, none was recorded in Sullivan County, and one was recorded within the WOH Watershed in Greene County. The three Delaware County and one Greene County seismic events had a magnitude less than 3.0 and are classified as “minor - not felt.” Table 4.2 of the RDSGEIS lists the magnitude of one of the Delaware County events as <2.0 and two of the events as between 2.0 and 2.9.

Three very small seismic events in the vicinity of the WOH NWI with magnitudes less than 3.0 recorded over the course of 39 years could be dismissed as inconsequential, due to human activity such as quarry blasts, or due to random noise. The seismic events are too small to be felt or to cause damage to structures at the surface, and their locations and depths could not be determined with accuracy. A magnitude 4.0 earthquake with a hypocenter depth of 13 km was recorded in 1991 in western Schoharie County, about 38 and 45 miles northeast of the East Delaware and West Delaware Tunnels, respectively. Historic earthquakes that produced perceptible, but not damaging, levels of ground motion were reported in 1852 (Intensity V, estimated magnitude 3.8), 1855 (Intensity V, estimated magnitude 3.8), and 1965 (Intensity IV, estimated magnitude 3.1) and were located southeast, east, and south, respectively, of the WOH Watershed.⁷⁴

The data for Delaware County seismic events were obtained from the LCSN database for 1970-2011,⁷⁵ and are presented in Table 7.1.

Table 7.1 Earthquake Data from LCSN Database for Delaware County

Date	Time	Lat	Lon	Depth	Mag
1977-03-27	12:34:54.0	42.120	-74.710	0	0.0
1982-06-12	19:26:03.5	42.286	-74.603	6	2.4
2001-01-15	00:28:47.0	42.110	-74.960	0	2.0

Because the seismic events recorded in Delaware County are very low in magnitude and not located near recording seismograph stations, the event epicenters and depths are not well constrained. The epicenters and depths determined for such small, poorly constrained seismic events can be in error by several kilometers.

The 0 km depths for the 1977 and 2001 seismic events indicate that either the events were due to human activities such as quarry or mine blasts, or they were very shallow events with poor depth resolution. The magnitude 0.0 for the 1977 event indicates that it was extremely small and barely detectable, and the fact that the event occurred during the noon hour suggests that it could have been

⁷⁴ Weston Geophysical Corporation, 2002

⁷⁵ <http://almaty.ldeo.columbia.edu:8080/data.search.html>

caused by human activities. There are several surface bluestone quarry operations in Delaware County, and it is possible that the event was related to a quarry blast. The 2001 magnitude 2.0 seismic event occurred shortly after midnight and is not likely to have been caused by a quarry blast. The 1982 magnitude 2.4 seismic event occurred in the evening, was assigned a depth of 6 km, and is likely an earthquake. We conclude that two of the three small seismic events likely were natural earthquakes.

The LCSN-determined epicenters for recorded seismic events in the vicinity of the WOH NWI are plotted on Figure 1 with an arbitrary 5-km zone of uncertainty drawn to emphasize the fact that the actual epicenter locations are not known with accuracy. There is simply not enough information to determine the uncertainty of the epicenter locations. The 1977 event is plotted for completeness. Such poorly constrained seismic events should not be attributed to movement on a specific fault or fault system, and we do not do so here, but earthquakes do occur on faults.

The LCSN-determined epicenters for the 1977 and 2001 small seismic events plot near the east and west ends of the Pepacton Reservoir, respectively. Seismologists would not place any reliance on the plotted locations due to the large uncertainty in the determination of the event epicenters and the fact that one of the events could possibly have been caused by human activity such as a quarry blast. The probability of reservoir-induced seismicity causing those seismic events is extremely low. Reservoir-induced seismicity is the triggering of earthquakes by the physical processes that accompany the impoundment of large, deep surface water reservoirs and is a well-documented phenomenon.^{76, 77, 78} Reservoir-induced seismicity is generally recognized during or shortly after filling periods of new surface water reservoirs, and the Pepacton Reservoir was filled in 1954, decades before the 1977 and 2001 seismic events. The LCSN has been operating since about 1970, so records for very small seismic events in Delaware County prior to that time are not available. Historic records of seismic events are based on “felt” events and reports of damage, and there are no records of such in the immediate vicinity of the Pepacton Reservoir prior to 1970.⁷⁹

Crone and Wheeler⁸⁰ of the USGS note that “earthquakes occur on faults, so the occurrence of earthquakes in a region is seismological proof that movement is occurring on faults, therefore, Quaternary tectonic faulting is occurring.” (The geologic term Quaternary means recent.) As noted previously in Section 7.4, Jacobi⁸¹ concludes that almost all of the seismic events in the Appalachian Basin portion of New York State can be correlated with known and suspected faults, and that it appears that more faults in New York State are seismically active than previously thought. He notes that “these seismically active faults crisscross a large portion of NYS.” The magnitude 4.0 earthquake at a depth of 13 km recorded in 1991 in western Schoharie County, about 38 and 45 miles northeast of the East Delaware and West Delaware Tunnels, respectively, indicates the

⁷⁶ Gupta, 2002

⁷⁷ USGS Auburn Project Review Team, 1996

⁷⁸ Simpson, et al., 1988

⁷⁹ Weston Geophysical Corporation, 2002

⁸⁰ Crone and Wheeler, 2000

⁸¹ Jacobi, 2002

presence of a seismically active fault in the general region. The seismicity data for the immediate vicinity of the WOH NWI are limited to three very small events, at least one of which could have been caused by a quarry blast, but they raise the possibility that one or more faults in the vicinity of the WOH NWI is seismically active.

2.5 Gravity and Aeromagnetic Data Near the WOH Non-Watershed Infrastructure

Extensive gravity and aeromagnetic data in the United States acquired by many investigators (including one of the authors⁸² of this document) have been compiled in a database available at a USGS website, accessible through the University of Texas El Paso website, UTEP.com, and described by Hildenbrand⁸³ and Hinze.⁸⁴ The aeromagnetic database is described as follows:

“The digital magnetic anomaly database and map for the North American continent is the result of a joint effort by the Geological Survey of Canada (GSC), U.S. Geological Survey (USGS), and Consejo de Recursos Minerales of Mexico (CRM). This integrated, readily accessible, modern digital database of magnetic anomaly data is a powerful tool for further evaluation of the structure, geologic processes, and tectonic evolution of the continent and may also be used to help resolve societal and scientific issues that span national boundaries. The North American magnetic anomaly map derived from the digital database provides a comprehensive magnetic view of continental-scale trends not available in individual data sets, helps link widely separated areas of outcrop, and unifies disparate geologic studies.

“The group created three unique, gridded data sets used to make the magnetic anomaly map of North America. Details on the data processing and compilation procedures used to produce the grids are described in the booklet that accompanies the North American magnetic anomaly map. The first grid shows the magnetic field at 305 meters above terrain. For the second grid we removed long-wavelength anomalies (500 km and greater) from the first grid. This grid was used for the published map. The third grid uses an equivalent source method, based on long-wavelength characterization using satellite data, to correct for spurious shifts in the original magnetic anomaly grid. Further details on the grids are described in the open-file report listed below.”

Details of the grids and a portal for accessing the grids are provided in USGS Open File Report 02-414.

The strength of gravity at the Earth’s surface responds to differences in subsurface density as well as other variables such as height, latitude, and several others. These effects are well known and are discussed in most if not all introductory texts.^{85,86} Removal of the “other effects” from the measured

⁸² Simmons, 1964

⁸³ Hildenbrand, 2002

⁸⁴ Hinze, et al., 2005

⁸⁵ Reynolds, 2011

⁸⁶ Burger, 2006

value of gravity provides results that can be interpreted in terms of subsurface density, and some spatial changes in density can be interpreted in terms of faulting.

The Earth's magnetic field is analogous to that of a bar magnet roughly coincident with the Earth's axis of rotation with perturbations due to subsurface magnetic materials, rocks and soils. Some rocks are more magnetic than others, and the resulting magnetic effects (anomalies in geophysical jargon) can be used to characterize the distribution of such rocks and sometimes to detect and characterize faults. The methods of measurement of magnetism and the interpretation of magnetic data are well known and are discussed in most if not all introductory texts.^{87, 88}

As part of the preparation for this Technical Memorandum, Hager-Richter accessed the USGS website, downloaded the gravity and aeromagnetic data, and plotted the gravity and aeromagnetic data for the area near the WOH NWI. The gravity plot is dominated by the northeast trending Scranton Gravity High shown in the Jacobi paper⁸⁹ and Weston Geophysical Corporation report.⁹⁰ The plots do not indicate the presence of faults or fractures in addition to those described in previous sections.

On the basis of regional aeromagnetic data supplemented with gravity data, King and Zietz⁹¹ described in 1978 a lineament that extends from New York to Alabama and interpreted the lineament in terms of a "profound discontinuity in the crystalline basement that underlies the Paleozoic sedimentary rocks of the Appalachian basin." Steltenpohl et al.⁹² used additional aeromagnetic and gravity data, "new borehole information, seismic surveys, and advances in geometric and kinematic analyses" acquired in the intervening 30+ years to interpret the lineament as due to "a crustal-scale strike-slip fault that has displaced anomalies attributed to Grenville orogenesis by ~220 km." The fault is very active seismically in Tennessee, and King and Zietz state "Modern eastern North American intraplate stresses today appear to be concentrating seismicity even nearer to the NY-AL lineament with time, implying the potential emergence of a throughgoing fault with future large earthquakes that exceed the historical record (Powell et al., 1994⁹³)." The projected location of the NY-AL lineament is west of the Scranton Gravity High shown in Jacobi's 2002 paper and the area of the WOH NWI plotted on Figure 1.

⁸⁷ Reynolds, 2011

⁸⁸ Burger, 2006

⁸⁹ Jacobi, 2002

⁹⁰ Weston Geophysical Corporation, 2002

⁹¹ King and Zietz, 1978

⁹² Steltenpohl, et al., 2010

⁹³ Powell et al., 1994

Section 3: Microseismicity Associated with HVHF

3.1 Introduction

The microseisms associated with HVHF are routinely monitored and used to determine the location of the fractures produced during HVHF, providing data thereby that can be used in real time to evaluate and control the HVHF process.^{94,95,96} However, the events are very small, requiring at least for some locations geophone arrays in one or more boreholes (10 - 20 three-component receivers) or 500+ surface geophones to obtain an adequate signal-to-noise (S/N) ratio to use the signals received on or near the surface. HVHF is performed along segments of the borehole laterals of a horizontal borehole as used in shale gas plays, and may be repeated multiple times during the productive life of a well.

3.2 Potential Impact on WOH Non-Watershed Infrastructure of HVHF Generated Microseisms

The questions to which this section seeks to answer are:

- Can such low amplitude events impact adversely the WOH NWI?
- Can such low amplitude events repeated possibly thousands of times impact adversely the WOH NWI?

In other words, what is the effect of a single low amplitude event and what is the effect if such an event is repeated multiple times?

3.2.1 Amplitude Effects

The amplitudes of microseisms due to HVHF stimulation of a shale gas well are extremely small. As an example, we use the data reported by Eisner et al.⁹⁷ for an event with magnitude estimated to be less than about -1.5 recorded during hydraulic fracturing. Although no units for the amplitudes of the events in their plot of the events in Figure 8 are shown, Eisner states in an email that the amplitude of the maximum event shown in their Figure 8 is approximately 400 nm/s. The body wave magnitude, m_b , given by $m_b = \log_{10} (A/T) + Q_h(h, \Delta)$ where A is the actual ground motion amplitude in micrometers (μm), T is the corresponding period in seconds (s), and Q is a correction for depth h and distance from the epicenter Δ .^{98,99} The value of Q is zero because (1) it is essentially a correction for attenuation between the epicenter or hypocenter and the recording station and (2) the

⁹⁴ Eisner, et al., 2010

⁹⁵ Duncan and Williams-Stroud, 2009

⁹⁶ Maxwell, 2011

⁹⁷ Eisner, et al., 2010

⁹⁸ Lay and Wallace, 1995

⁹⁹ Shearer, 2009

distances between the hypocenter and the recording geophones for the case reported by Eisner et al. are sufficiently small to have little to no effect. Using the equation for m_b , velocity of 400 nm/s, and a frequency of 20 Hz, the magnitude of a “large”¹⁰⁰ microseism due to HVHF is approximately $m_b = -1.7$. The value of A/T , effectively peak particle velocity (PPV) as the term is used in the vibration literature, is 4.0×10^{-5} cm/s, 400 nm/s. This value applies at the earth’s surface, and because the WOH NWI of interest to this document is typically several hundred feet below the surface, the vibration level at the tunnel depth would be even smaller. The periods of the signals reported by Eisner et al. are 20-30 ms, frequencies of 33-50 Hz.

Can seismic events of such low magnitude affect the WOH NWI? Some guidance in answering this question can be had from the literature on vibrations due to blasting and other construction activities.¹⁰¹ The generally accepted threshold for creating cosmetic damage to surface structures is 20-200 mm/s, 50,000-500,000 times larger than the amplitude of microseisms due to routine HVHF activities. For surface structures, cosmetic damage is damage that affects the appearance but not the integrity of structures. Such damage is commonly hairline cracks in the walls around windows and doors, many of which are caused by such phenomena as building settlement and door slams. For the WOH water supply tunnels at depth, such damage would not be expected to occur. On this basis, it appears that the vibrations from individual and even multiple microseismic events due to routine HVHF activities are not likely to damage the tunnels.

3.2.2 Effects of Repetition

As noted above, HVHF operations are repeated many times during the life of a shale gas well, subjecting nearby objects to repeated impacts of microseismic waves. With dense drilling of gas wells with multiple horizontal laterals, HVHF operations could occur perhaps several thousands of times in the vicinity of the WOH NWI. There appears to be no publications on the effects of microseisms on tunnels, and we turn to the literature on vibrations due to construction activities for guidance. Dowding¹⁰² states on p. 175:

“In material testing such degradation [i.e., damage] through repeated loading is called fatigue.”

“Most of the fatigue evidence comes from laboratory tests such as those conducted by Leigh (1971) to investigate the effects of repeated sonic booms on plaster. Leigh’s experimental panels were made of poured molding plaster, 0.4 m (16 in) square by 9.5 mm (3 in) thick and were deformed by a continuous 5- to 7-Hz air pressure pulse. His work, presented in Figure 12-6, showed that if panels were loaded (strained) to 60% of their static capacity, 84% of the panels would not crack until 4,000 loading cycles had been reached. The 84% is found at the intersection of the lower dashed line and 60% of the static strength. Similar tests conducted on plasterboard stripped of its paper backing confirmed this trend (Dowding et al., 1980).” p.175.

¹⁰⁰ The language of Eisner L, et al., 2010

¹⁰¹ Dowding, 2000

¹⁰² Dowding, 2000

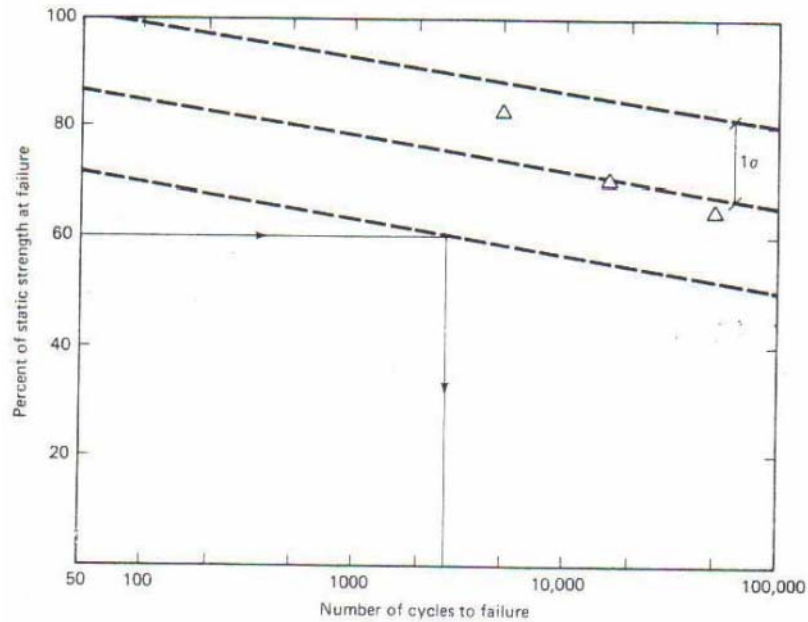


Figure 12-6 Fatigue behavior of gypsum panels. (After Leigh, 1974.)

Dowding continues:

“ The U.S. Bureau of Mines has conducted two studies on full-size homes that provide insight into the effects of fatigue. The most recent showed no effects until 52,000 cycles for vibration at an equivalent particle velocity measured in the ground of 12.5 mm/s (0.05 in/s), and will be discussed in detail in the next section.” p. 176

Dowding describes tests on a house built specifically for testing vibrations by the U.S. Bureau of Mines. The house was shaken by a device with a vibration equivalency of about 0.3 to 1.0 Hz. The first fatigue cracks occurred at about 52,000 cycles.

On the basis of such tests, it is apparent that fatigue due to repetitive vibrations can cause damage even though a single event or a few events do not cause the same damage. We note explicitly that the vibration amplitudes and frequencies used for the tests are more severe than those expected at the WOH NWI due to hydraulic fracturing. For comparison of amplitudes: 0.1 to 1.0 mm/s for fatigue testing versus 0.1×10^{-3} to 1.0×10^{-3} for hydraulic fracturing, three orders of magnitude difference. For comparison of frequencies: 4 to 40 Hz for fatigue testing versus 100 to $n \times 100$ Hz for hydraulic fracturing, one order of magnitude difference.

There are many unknown parameters needed for a better analysis of the probability of damage to the WOH NWI due to repeated HVHF operations, including but not limited to the current condition of the concrete liners and the smallest allowable distance from a tunnel for drilling, and rock properties (especially attenuation).

3.3 Documented Tunnel Failures Due to Earthquakes

In this section, we explore data on tunnels damaged during earthquakes. Tunnel failures due to earthquakes were documented in a 1991 publication,¹⁰³ with 192 reports for 85 earthquakes worldwide.

The analysis of the distribution of tunnels damage with respect to (1) magnitude (obtained for some events with the Gutenberg and Richter relation between intensity and magnitude¹⁰⁴) and (2) epicentral distance are useful to consider. However, sufficient data for analysis were available in 1991 for only 132 cases, summarized in Figure 2. The magnitude plot shows clearly that most of the earthquakes were large and that the larger the earthquake, the more severe the damage. The epicentral distance plot shows a similar trend in that the smaller the epicentral distance, the more severe the damage.

For $M_L < 4$, the extent of damage was 3, 2, 1, and 1 for damage categorized as none, slight, moderate, and heavy, respectively. For epicentral distance less than 25 km, the extent of damage was 20, 30, 13, and 7 for damage categorized as none, slight, moderate, and heavy, respectively. For epicentral distance of at least 25 km but less than 150 km, the extent of damage was 60, 14, 9, and 11 for damage categorized as none, slight, moderate, and heavy, respectively.

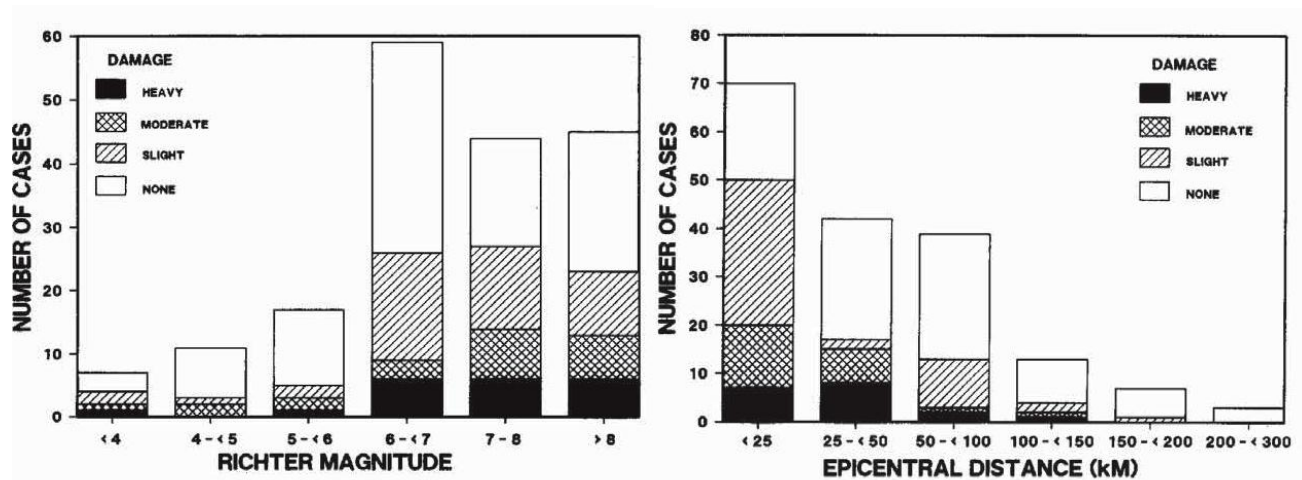


Figure 2. Effects of epicentral distance and earthquake magnitude on damage. (After Sharma and Judd¹⁰⁵)

¹⁰³ Sharma and Judd, 1991

¹⁰⁴ Gutenberg and Richter, 1954

¹⁰⁵ Sharma and Judd, 1991

Although the damage categories were not explicitly defined, Sharma and Judd state that they were based “on such reported observations as:

- (1) opening deformation;
- (2) occasional rock falls from roof;
- (3) roof or wall collapse;
- (4) displacement along intersecting faults;
- (5) slabbing or spalling of the rock around the opening;
- (6) displacement or deformation of supports or lining.”

It would appear that minor cracking – which could be significant for the unreinforced concrete linings of the WOH NWI – was not considered to indicate failure.

On the basis of those data, however, it appears that:

- *Tunnels can be damaged by seismic events with magnitudes less than 4.*
- *Tunnels can be damaged by seismic events on faults located at distances up to 150 km from the tunnel.*

3.4 Earthquakes of Small Magnitude Associated with HVHF

Section 6.13.2 of the RDSGEIS states “The possibility of fluids injected during hydraulic fracturing the Marcellus or Utica Shales reaching a nearby fault and triggering a seismic event are remote for several reasons. The locations of major faults in New York have been mapped (Figure 4.13) and few major or seismically active faults exist within the fairways for the Marcellus and Utica Shales....It is Alpha’s opinion that an independent pre-drilling seismic survey probably is unnecessary in most cases because of the relatively low level of seismic risk in the fairways of the Marcellus and Utica Shales. Additional evaluation or monitoring may be necessary if hydraulic fracturing fluids might reach a known, significant, mapped fault, such as the Clarendon-Linden fault system” We examine these statements and Alpha’s opinion below in this section on the basis of data, some of which have only recently become available.

The RDSGEIS states that hydraulic fracturing has not caused earthquakes,¹⁰⁶ but recently released research demonstrates otherwise. As discussed in Sections 3.4.1 and 3.4.2 below, there is now one example of a small earthquake conclusively attributed to HVHF operations at a shale gas site near Blackpool, UK,¹⁰⁷ and a second example that is likely due to HVHF operations in a shale gas field in Garvin County, Oklahoma.¹⁰⁸

¹⁰⁶ Alpha, 2009

¹⁰⁷ de Pater and Baisch, 2011

¹⁰⁸ Holland, 2011

3.4.1 Preese Hall Well, Lancashire, UK — New Evidence that Hydraulic Fracturing can cause Earthquakes

The first conclusive case of HVHF stimulation of a shale gas well triggering seismic events on a previously unknown/unmapped fault has been documented for a site in the UK in a report released on November 2, 2011. The study, entitled “Geomechanical Study of Bowland Shale Seismicity,”¹⁰⁹ reports the results of a comprehensive multidisciplinary investigation commissioned by the owner of the well, Cuadrilla Resources Ltd, to study the relationship between Cuadrilla’s operations and two earthquakes that occurred in 2011 near the Preese Hall well site in Lancashire County, near Blackpool, UK. Two small earthquakes of M_L 2.3 and 1.5 occurred in 2011 near the Preese Hall well.

The Preese Hall well is located in an area of very low seismicity. The well is vertical and was drilled for shale gas to a total depth of about 9084 ft, landing in the target shale. Cores of the shale and an extensive suite of logs were used to measure rock properties and the in situ stress tensor, and the difference in maximum and minimum horizontal stress is about 4,000 psi. The local stress regime was determined to be that of strike slip faulting. The 5½” production casing was perforated in six zones between 7670 ft and 8949 in the Lower Bowland Shale formation.

Five fracture treatments were pumped in April and May, 2011, with the largest stage having a volume of 14,000 bbl of water and a proppant (sand) mass of 117 tonnes.

Seismic events occurred after two HVHF treatments of the well and were reported by the British Geological Survey to have magnitudes of 2.3 and 1.5. As in the case of the Delaware County events discussed in Section 2.4 of this Technical Memorandum, the locations and depths of the earthquakes were not well constrained due to the small size of the events and the distance from the recording seismograph stations. After the first seismic event was detected at regional seismic stations, several local stations were established near the site to acquire data for better resolution of hypocenter locations. The correlation in time of seismic events and hydraulic fracture activity is very striking, leaving no doubt that the seismic events were directly related to the HVHF activity.

One fault is located near the well, as shown in a figure labeled “Reprocessed seismic section.” The report indicates that the fault was unknown before reprocessing the seismic data. The report attributes the earthquakes to injection of the HVHF liquid into a fault and for a M_L 2.3 event assigns a shear area of “the order of at least several 10,000 m².”

The authors analyzed geological conditions, 50 small earthquake events recorded during HVHF treatment, reprocessed seismic reflection data, geophysical well logs, cores, rock properties, and regional stress conditions as well as the drilling and HVHF treatment records. They conclude that the repeated seismicity was likely induced by direct injection of a high percentage of the HVHF fluid into the same fault zone, which had not been previously mapped and which does not extend to the earth’s surface. The authors estimate that the HVHF fluids migrated as much as 2,000 feet upward along the fault. They consider the site a worst-case scenario because the induced seismicity

¹⁰⁹ de Pater and Baisch, 2011

requires three conditions that are rarely present at once: 1) a critically stressed fault, 2) a fault that is transmissible enough to accept large quantities of fluid, and 3) a fault that is brittle enough to fail seismically. They further conclude that the likelihood of encountering similar conditions elsewhere in the area of the Preese Hall well is low.

The authors of the Bowland Gas Seismicity study used models to predict that a maximum ‘worst case’ magnitude 3.0 seismic event could be caused by injections of fluids during HVHF treatments. Events of such a low magnitude would not cause damage to surface structures. They suggest mitigation mechanisms to minimize future seismic events – rapid fluid flow back after the HVHF treatments and reducing the HVHF treatment volume. They recommend avoiding HVHF treatment of intervals close to a fault (as identified with image logs during continuous well logging) and seismic monitoring during HVHF injection.

3.4.2 Possible HVHF Induced Seismicity in Garvin County, Oklahoma

The Oklahoma Geological Survey (OGS) recently investigated possible HVHF-induced seismicity in the Eola Field of Garvin County, Oklahoma.¹¹⁰ The Oklahoma case is similar to the UK case of HVHF induced seismicity discussed in Section 3.4.1 of this Technical Memorandum in that there was a clear temporal correlation between the time of HVHF treatment and the occurrence of measurable seismicity. Forty-three earthquakes that ranged in magnitude from 1.0 to 2.8 occurred within about 24 hours during HVHF stimulation of a vertical gas well in Garvin County.

The Oklahoma case is also similar to the induced seismicity in the Bowland Shale in the UK and the historic Delaware County seismicity reported in Section 2.4 of this Technical Memorandum in that the locations and depths of the seismic events could not be well constrained due to their low magnitudes and the distance to the nearest seismograph recording station. Several faults are present within 3 km of the vertical well that was hydraulically fractured, but uncertainties in hypocenter locations of 300-500 m are too large to determine which fault(s) were the locations of the earthquakes. Previous earthquakes were known to have occurred in the vicinity. The OGS determined that the majority of the earthquakes occurred within about 3.5 km of the vertical well that was HVHF stimulated, had the seismic signatures of shallow events, and that about 95% of the events could be modeled using a simple pore pressure diffusion model of the HVHF fluids.

The OGS found that the temporal correlation of HVHF treatment and the earthquakes and the reasonable fit to a simple physical model suggest that “there is a possibility the earthquakes were induced by hydraulic-fracturing. However, the uncertainties in the data make it impossible to say with a high degree of certainty whether or not these earthquakes were triggered by natural means or by the nearby hydraulic-fracturing operation.”

¹¹⁰ Holland, 2011

3.4.3 Comment on the RDSGEIS Assessment of Earthquakes of Small Magnitude Associated with HVHF

The Blackpool earthquakes and probably the Oklahoma earthquakes demonstrate that hydraulic fracturing fluids can reach a nearby fault and can trigger a seismic event. Therefore, the RDSGEIS statement that “The possibility of fluids injected during hydraulic fracturing the Marcellus or Utica Shales reaching a nearby fault and triggering a seismic event are remote for several reasons ”is not consistent with recent evidence of HVHF-induced seismic events.

Section 4: Potential for Reactivation of a Fault by HVHF Near the WOH Non-Watershed Infrastructure

4.1 Introduction

The discussion in Section 2.2 of this Technical Memorandum concludes that Figure 4.13 of the RDSGEIS is not sufficient to characterize faulting present in the vicinity of the WOH NWI. The data compilation in Figure 1 shows that several faults are present in the vicinity of and cross the WOH NWI. There is no geophysical documentation to indicate that the faults mapped in the water supply tunnels do not extend to the depths of the Marcellus Shale, and similar faulting has been described in the Marcellus in Pennsylvania.^{111,112} The discussion of seismicity in Section 2.4 of this Technical Memorandum raises the possibility that one or more faults in the region of the WOH NWI is seismically active.

The WOH NWI is a critical facility that transports unfiltered water to half the population of the State of New York. The faults mapped in the water supply tunnels are now “known” and “mapped,” and they are “significant” because they cross a critical facility.

Given the mapping data shown in Figure 1, vertical or horizontal drilling in the vicinity of the WOH NWI very likely could intersect one or more faults. Although Section 6.13.2 of the RDSGEIS notes that “the geologic conditions associated with a fault generally are unfavorable for hydraulic fracturing and economical production of natural gas” and “as a result, operators typically endeavor to avoid faults for both practical and economic considerations,” it seems obvious that “additional evaluation and monitoring may be necessary” for development of a horizontal well that could intersect one of the “known, significant, mapped faults” that cross the WOH NWI.

Is it possible that HVHF stimulation could trigger a seismic event on a fault that intersects or is near the WOH NWI? Section 6.13.1 of the RDSGEIS notes that thousands of shale gas wells have undergone HVHF treatment in the US without triggering earthquakes, but the recently released research discussed in Sections 3.4.1 and 3.4.2 of this Technical Memorandum has shown that HVHF stimulation of a shale gas well triggered earthquakes of small magnitude in the UK and likely did so in Oklahoma in 2011. Whether HVHF treatment helped trigger additional seismic events along faults in other gas plays where natural seismic activity occurs has not been proven. *The newly released research raises the possibility, however small, that HVHF treatment of horizontal boreholes in the vicinity of the WOH NWI could induce one or more earthquakes that the unreinforced concrete lined water supply tunnels would not experience otherwise.*

Section 6.13.2 of the RDSGEIS states:

“Seismic monitoring by the operators is performed to evaluate, adjust, and optimize the hydraulic fracturing process. Monitoring beyond that which is typical for hydraulic

¹¹¹ Yang and Morris, 2011

¹¹² Hulsey, et al., 2010

fracturing does not appear to be warranted, based on the negligible risk posed by the process and very low seismic magnitude. The existing and well-established seismic monitoring network in New York is sufficient to document the locations of larger-scale seismic events and would continue to provide additional data to monitor and evaluate the likely sources of seismic events that are felt.”

As shown in the discussions of seismicity in Delaware County in Section 2.4 of this Technical Memorandum and in Sections 3.4.1 and 3.4.2 regarding seismicity induced or possibly induced by HVHF stimulation in the UK and Oklahoma, regional seismic monitoring networks are too distant to provide precise location and depth data for the recorded small seismic events. Seismic monitoring networks in New York are installed primarily to monitor seismicity for understanding hazards from natural seismicity rather than to monitor induced seismicity due to HVHF stimulation of shale gas wells. Although the WOH NWI is located in a region of low natural seismicity, low seismicity does not necessarily mean that induced seismicity will not occur. Additional seismic monitoring stations coupled with microseismic monitoring routinely used as a remote sensing tool for engineering and measuring the success of HVHF stimulation could provide information to assess stress redistribution and possible induced seismicity.

The discussion of joints, faults, and lineaments in Section 2.2 of this Technical Memorandum shows that *the subsurface formations underlying the critical WOH NWI are likely more complexly fractured by jointing and faulting than indicated in the RDSGEIS, but they are not well characterized in the vicinity of the WOH NWI.* Obtaining as much information as possible about the subsurface stress field is critical for engineering HVHF stimulation and in assessing the potential for induced seismicity in any area, but detailed site specific geophysical data for the WOH NWI region are not available. *The absence of direct geophysical data from borehole logging and high resolution seismic reflection surveys, and the natural complexity in rock properties all contribute to the uncertainty in understanding the contemporary stress field and the possible presence of critically stressed faults in the vicinity of the WOH NWI.*

4.2 Could Seismic Events Induced by HVHF Cause Damage to the Critical WOH Non-Watershed Infrastructure?

Even if seismicity induced by HVHF treatment does occur along faults in the vicinity of the WOH NWI, the HVHF-induced seismic events as discussed in Sections 3.4.1 and 3.4.2 above are quite small. Could such seismic events induced by HVHF stimulation cause damage to the critical WOH NWI?

In the analysis of differential pressure required to damage unreinforced concrete lined tunnels such as the West Delaware Tunnel, Jenny Engineering Corporation determined that 10-20 psi differential pressure would be sufficient.¹¹³ Whether the movement associated with the M_L 2.3 event generated by the HVHF treatment of the Preese Hall well located in Lancashire County near Blackpool, UK, described by de Pater and Baisch,¹¹⁴ would be sufficient to cause such differential pressure depends

¹¹³ Jenny Engineering Corporation, 2009

¹¹⁴ de Pater and Baisch, 2011

on details at the intersection of the fault and the tunnel. Such details include but are not limited to the strength and elastic properties of the rock and concrete, the width of the fault, whether the fault is a single plane or a fault zone filled with gouge, and whether the outer tunnel wall is in intimate bonded contact with the adjacent rock everywhere within 10-20 ft of the intersection. Unfortunately, such details are not available at this time.

However complex the details of the engineering problem of determining the stress on the tunnel due to movement on the fault, determining the amount of movement from the earthquake magnitude is relatively simple. As discussed in Section 3, the various magnitudes are approximately equal (except for M_S) and we set $M_W = 2.3$. The seismic moment, M_O , is defined as $M_O = G * A * D$, where G is shear modulus, A is the area of a fault on which displacement D occurs.^{115,116} Using units for G , A , and D of dyn/cm², cm², and cm, respectively, the units for M_O are dyn-cm. The value of G is usually taken as 32 GPa (3.2E+24 dyn/cm²). The Moment Magnitude, M_W , is given^{117,118,119} by $M_W = 2/3 * \text{Log}_{10}(M_O) - 10.7$.

Using these equations, the area of slippage as 10,000 m², and $M_W = 2.3$, values given by de Pater and Baisch,¹²⁰ for the largest of the documented Preese Hall well related seismic events, the fault would move about 3/8 in. As indicated above, whether a 3/8-in. displacement on a fault intersecting the Delaware tunnel would damage the tunnel depends on several factors that are not known at this time. We note that some faults intersected by the tunnel were described as crushed rock, and expect that displacement of 3/8 in might have little to no effect on the tunnel. Similar displacement on other discrete faults, however, where gouge, brecciation, or crushed rock zones are absent might damage the tunnel.

At this time, there is not enough known about the state of stress and faulting in the vicinity of the WOH NWI and details about the condition of the unreinforced concrete lined tunnels of the WOH NWI to determine whether the tunnels would be damaged by an induced seismic event of the magnitude modeled above.

4.3 Could Seismic Events Induced by HVHF Damage the Critical WOH Dams?

Although the JV tasked Hager-Richter with assessing the potential impact of HVHF operations on the WOH NWI from a geophysical perspective, the same data and considerations used for that task also apply to assessing the potential impact of HVHF operations on the critical WOH dams from a geophysical perspective. In this section, we consider such impacts.

Even if seismicity induced by HVHF treatment does occur along faults in the vicinity of the WOH watershed dams, the HVHF-induced seismic events as discussed in Sections 3.4.1 and 3.4.2 above

¹¹⁵ Day, 2002

¹¹⁶ Elnashai and Di Sarno, 2008

¹¹⁷ Kanamori, 1977

¹¹⁸ Hanks and Kanamori, 1979

¹¹⁹ Day, 2002

¹²⁰ de Pater and Baisch, 2011

are quite small. Could such seismic events induced by HVHF stimulation cause damage to the critical WOH dams?

The context in which to answer this question is the risk analysis, technically called a probabilistic seismic hazard analysis (PSHA), of damage to the DEP Catskill/Delaware dams that could be due to naturally occurring earthquakes. A PSHA was conducted by Weston Geophysical Corporation¹²¹ (Weston) in 2002 for the six DEP Catskill and Delaware dams, and GZA¹²² performed a stability analysis of each dam and showed the factors of safety for each. In this section, we compare the peak ground accelerations that would be produced by an earthquake located on a shallow fault directly below a dam with the values determined by Weston and GZA.

The relation of earthquake magnitude to peak ground acceleration is a function of distance between the epicenter and the location of interest, the type of faulting that produced the earthquake, and attenuation. Many models of the attenuation relationships have been developed¹²³ using various databases. For this calculation, we have used three such relations: Ambraseys et al.,¹²⁴ Ambraseys et al.,¹²⁵ and Akkar and Bommer.¹²⁶ We have assumed that the dam is constructed on rock and the fault is very shallow.

On the basis of the results of the Blackpool, UK earthquakes¹²⁷ and the Garvin County, Oklahoma earthquakes,¹²⁸ we have used magnitudes of 2.3 and 3.0. Magnitude 2.3 is the largest event recorded for the Blackpool, UK earthquakes, and 3.0 is the maximum magnitude estimated by de Pater and Baisch for the worst case scenario for the Blackpool area for continued HVHF operations. The results are the following:

¹²¹ Weston Geophysical Corporation, 2002

¹²² GZA, 2003

¹²³ Srbulov, 2008

¹²⁴ Ambraseys et al., 2005a

¹²⁵ Ambraseys et al., 2005b

¹²⁶ Akkar and Bommer, 2007

¹²⁷ de Pater and Baisch, 2011

¹²⁸ Holland, 2011

	Mag	Fault Type	Peak Ground Acceleration	
Ambraseys et al., 2005a	2.3	Unknown	1.064 m/s/s	.109 g
	2.3	Normal or Strike Slip	0.877 m/s/s	.894 g
	3	Unknown	1.322 m/s/s	.135 g
	3	Normal or Strike Slip	1.089 m/s/s	.111 g
Ambraseys et al., 2005b	2.3	Unknown	0.330 m/s/s	.034 g
	2.3	Normal or Strike Slip	0.247 m/s/s	.025g
	3	Unknown	0.483 m/s/s	.049 g
	3	Normal or Strike Slip	0.362 m/s/s	.0037 g
Akkar and Bommer	2.3	Unknown	0.122 cm/s/s	.0001 g
	2.3	Normal or Strike Slip	0.101 cm/s/s	.0001 g
	3	Unknown	0.516 cm/s/s	.0005 g
	3	Normal or Strike Slip	0.427 cm/s/s	.0004 g

The values of peak horizontal ground acceleration determined in the PSHA of the Catskill/Delaware dams by Weston ranged between 8% g and 14% g for a probability of exceedance of 2% in 50 yrs. GZA relied on Weston's PSHA and "concluded that a horizontal acceleration of 0.12 g is applicable for design at all of the reservoirs," using an increased return period of 10,000 yrs.

Because the peak horizontal ground accelerations of earthquakes likely to be induced by HVHF are comparable to the values determined in the Weston PSHA and to the values recommended by GZA for the Catskill/Delaware dams, we conclude that the potential risk to the dams is no greater than the risk due to natural earthquakes.

Section 5: Adequacy of the Tunnel Protections Described in the RDSGEIS

This section presents an evaluation of the adequacy of protections described in the RDSGEIS for WOH NWI from a geophysical perspective. The sole protection specifically afforded to DEP water supply tunnels by the RDSGEIS is the requirement for an environmental site-specific review by the NYSDEC for any HVHF drilling operation located within 1,000 feet of a WOH NWI as measured from the wellhead to the tunnel centerline. In addition, those portions of the WOH NWI that fall within the NYC WOH Watershed and a 4,000-foot buffer around it or within State Forest Preserve lands would also be protected by a prohibition of HVHF drilling operations.

5.1 Brief History of RDSGEIS

NYSDEC issued a Generic Environmental Impact Statement (GEIS)¹²⁹ in 1992 to streamline processing of permit applications for oil and gas related drilling activities, rather than requiring a site-specific SEQRA (State Environmental Quality Review Act) review for each case. At the time of issuance of the GEIS, horizontal drilling and HVHF treatment were not common practice, and protocols established in the GEIS were designed with vertical drilling and low volume hydraulic fracturing in mind.

The advent of enhanced production techniques such as horizontal drilling and HVHF and their successful application to the Barnett Shale of Texas, the Fayetteville Shale of Arkansas, and other black shale gas plays helped lead to renewed interest in the Marcellus Shale,^{130,131} a black shale of Lower Devonian age that underlies much of southern and central New York State including the WOH Watershed region. HVHF coupled with horizontal drilling typically uses much more water per well than a vertically drilled well, and has the capability of accessing a greater subsurface volume from laterals drilled horizontally in a target formation. These and other developments led to increased potential environmental impacts that were not addressed in the 1992 GEIS.

In 2008, NYSDEC began work on a *Supplemental* GEIS (SGEIS) to address the additional environmental and socioeconomic concerns imposed by high volume hydraulic fracturing on a regional scale. A *Draft* Supplemental Generic Environmental Impact Statement (DSGEIS) was issued on September 30, 2009. After receiving comments and recommendations from various interested parties, NYSDEC issued the *Revised* Draft Supplemental Generic Environmental Impact Statement (RDSGEIS) on September 7, 2011. Comments on the RDSGEIS are due by January 11, 2012. The Final SGEIS will be issued thereafter.

The RDSGEIS applies to HVHF drilling operations, where water volumes used in the process exceed 300,000 gallons. Drilling operations using less than 300,000 gallons are subject to the 1992

¹²⁹ GEIS, 1992

¹³⁰ Bruner and Smosna, 2011

¹³¹ Harper, 2007

GEIS. In most cases, horizontal drilling and HVHF would be used for efficiently tapping the gas resources trapped in the Marcellus Shale,^{132,133} and such activities would operate under RDSGEIS.

5.2 Protections to NYC WOH Non-Watershed Infrastructure Provided by RDSGEIS

5.2.1 1,000-Foot Buffer

The RDSGEIS adopts protocols agreed upon by DEP and NYSDEC for siting geothermal wells that were primarily designed to protect the water supply tunnels from direct penetration by drilling. Under the protocol, NYSDEC will notify DEP of applications to drill gas wells in the counties outside NYC that contain WOH NWI. DEP will determine whether a proposed well location is within 1,000 feet of one of its water supply tunnels. Any proposed well location that NYCDEP determines to be outside of the 1,000-foot buffer zone would fall under the general provisions of the GEIS or RDSGEIS. Proposed well locations determined to be within the 1,000-foot buffer would be subject to a site specific SEQRA review. A negative declaration (i.e. a declaration that drilling would cause no significant environmental impact) would only be issued if DEP is satisfied that there would be no impact to tunnels and aqueducts.

5.2.2 Prohibition on HVHF Drilling in WOH Watershed and State Forest Preserves

Portions of the NYC WOH NWI would be protected by additional prohibitions described in the RDSGEIS. There is a prohibition on issuing permits for HVHF drilling within 4,000 feet of the WOH Watershed and within State-owned land administered by the DEC (the Constitution of NYS requires that State land administered by DEC, including state forest land, is to be kept “forever wild”). In addition, the RDSGEIS states that “Current Office of Parks, Recreation and Historic Preservation (OPRHP) policy would impose a similar restriction on State Parks.”¹³⁴

The prohibition on HVHF drilling activities within 4,000 feet of the WOH Watershed serves to protect all of the Shandaken Tunnel from such activities, but only small portions of the East and West Delaware and Neversink Tunnels and very small portions of the Catskill and Delaware Aqueducts fall within the 4,000-foot setback. Of these unprotected portions of tunnels, the East and West Delaware Tunnels have sizeable zones that fall outside of the protected WOH Watershed. Only limited portions of the tunnels fall within areas of the patchwork Catskills Forest Preserve, so significant portions of the tunnels outside of the WOH Watershed are not protected by the ban on HVHF. Thus, *the 1,000-foot buffer from well head to tunnel is the sole protection afforded to the WOH NWI.*

¹³² Bruner and Smosna, 2011

¹³³ Harper, 2007

¹³⁴ RDSGEIS, 2011

5.2.3 Deep Injection wells for Wastewater Disposal

HVHF drilling operations generate large volumes of wastewater per well. Options to deal with the large volumes of wastewater include recycling and reuse, treatment, and deep injection wells. Increasingly, oil and gas companies are developing techniques to reuse wastewater in subsequent hydraulic fracturing jobs. It is likely that given the expected level of HVHF drilling in NYS, and differing degrees of expertise among operators, significant amounts of hydraulic fracturing wastewater may still require disposal. Treatment facilities that could accept hydraulic fracturing wastewater are lacking in NYS, and it is unclear whether deep injection wastewater disposal would be viable in NYS.¹³⁵

The RDSGEIS does not address deep injection wastewater disposal wells. Instead, permits for deep injection wastewater disposal wells require site specific SEQRA review.¹³⁶

5.3 Justification of Proscribed Protections

NYSDEC adopted the 1,000-foot buffer based on previous protocols established primarily to address siting of geothermal wells.¹³⁷ NYSDEC and its consultant, Alpha Geoscience, present arguments that HVHF operations pose no significant impact to the WOH NWI. The validity of those arguments is discussed in Section 5.4.

The main geophysical reasons given in the RDSGEIS that protections greater than the 1,000 feet buffer are not deemed necessary are as follows:

- Faults are not documented in the WOH Watershed region and there is low seismic risk;
- HVHF has not been linked to earthquakes;
- HVHF is confined to the target formation;
- The fracture barrier strata between the Marcellus Shale and the DEP WOH water supply tunnels will prevent damage to the tunnels; and
- The Marcellus itself is a low permeability shale and is isolated from overlying strata.

In Section 5.4, we will examine several aspects of this evidence, especially that evidence pertaining to faults in the WOH Watershed region and the link between hydraulic fracturing and earthquakes.

¹³⁵ FIA, 2009

¹³⁶ RDSGEIS, 2011

¹³⁷ RDSGEIS, 2011

5.4 Analysis of Evidence Presented in the RDSGEIS

5.4.1 Faults and Brittle Structures in the WOH Watershed Region

5.4.1.1 Previously Documented Faults and Brittle Structures

The title of Figure 4.13 in the RDSGEIS, “Mapped Geologic Faults in New York State” and the associated statement in Section 4.5.1 of the RDSGEIS, “Figure 4.13 shows the locations of faults and other structures that may indicate the presence of buried faults in New York State,” are misleading. The figure was modified from work by Isachsen and McKendree¹³⁸ by omitting topographic/tonal linear features interpreted by the authors as brittle structures. Topographic/tonal features are surface lineaments identified on aerial photographs, satellite imagery, and maps. Lineaments can be the surface expression of faults at depth.^{139,140,141,142} In its response to the JV’s 2009 FIA, Alpha indicates that the omission of topographical/tonal features on the map presented by the RDSGEIS is justified on the basis that such features have not been confirmed in the field, that there is no proof that any fracture or fault extends deep enough to intersect the Marcellus, and that the map was labeled by the authors as preliminary.¹⁴³ They also cite an oral presentation of Engelder, who states that the use of lineaments to map crustal faults is highly controversial.¹⁴⁴

It is correct that not all lineaments identified from aerial photographs or satellite imagery are later demonstrated by field mapping to be faults or fractures. However, the use of lineaments from aerial photographs, satellite data, etc. is widely recognized as a valuable tool for identifying possible fault and fracture zones, and numerous studies have shown good correlations between lineaments and mapped faults.^{145,146,147,148} Jacobi, 2002 states: “Perhaps the single most important study that advanced the recognition of faults in NYS was the identification of lineaments in 1997 by Earth Satellite Corporation (EARTHSAT) on Landsat Thematic Mapper (TM) images...”¹⁴⁹

The 2009 FIA produced by the JV examined the locations of faults and brittle structures recorded during the construction of the tunnels, and found that several fault zones correlate with surface lineaments documented in Isachsen and McKendree.¹⁵⁰

¹³⁸ Isachsen and McKendree, 1977

¹³⁹ Jacobi, 2002

¹⁴⁰ EarthSat, 1997

¹⁴¹ Hill et al., 2002

¹⁴² Morelli and Piana, 2006

¹⁴³ Alpha, 2009

¹⁴⁴ Engelder, 2010

¹⁴⁵ Jacobi, 2002

¹⁴⁶ EarthSat, 1997

¹⁴⁷ Hill et al., 2002

¹⁴⁸ Morelli and Piana, 2006

¹⁴⁹ Jacobi, 2002

¹⁵⁰ Isachsen and McKendree, 1977

Jacobi mapped faults in New York State based on Landsat data, geophysical, and earthquake data.¹⁵¹ Two N-S trending faults that extend south from the previously mapped Sprakers and Noses Faults through Delaware County into the northern portions of Sullivan and Ulster Counties were proposed. The proposed western fault that extends southward from Sprakers Fault crosses the East and West Delaware Tunnels. Jacobi's proposed extension of the Noses Fault nearly crosses the tunnel alignments.

5.4.1.2 Analysis of Orthoimagery

As presented in Chapter 4, we examined high resolution orthoimagery acquired by DEP in the WOH Watershed and along the East Delaware, West Delaware, and Neversink Tunnels. We interpreted additional projected possible faults that cross the tunnel alignments. The possible faults coincide in part with lineaments identified previously^{152,153,154} and with faults and brittle features encountered during tunnel construction.¹⁵⁵

5.4.1.3 Earthquakes and Seismicity

Naturally occurring earthquakes in New York State have been monitored by the Lamont-Doherty Cooperative Seismic Network since 1970. As discussed in Section 2.4, three small seismic events have been recorded in the immediate vicinity of the WOH Watershed in Delaware County, and one magnitude 4.0 earthquake was recorded in western Schoharie County north of the WOH Watershed. As discussed in Section 2.4, the fact earthquakes have occurred in the vicinity of the WOH NWI, even if too small to be felt or cause damage to structures at the surface, raises the possibility that one or more seismically active faults is present in the region.

5.4.2 HVHF Drilling Operations and Microseismicity

Section 3 of this Technical Memorandum discusses in greater detail HVHF induced microseismicity. The RDSGEIS reports that Alpha contacted seven researchers familiar with seismic activity in New York and Texas, and that none of them had any knowledge of seismic activity attributed to hydraulic fracturing. Several cases where seismic activity was tentatively linked to HVHF later turned out to be the result of deep injection wells.^{156,157,158} Recently, however, seismic events of magnitudes 2.3 and 1.5, as well as numerous smaller events have been conclusively linked to HVHF operations in a shale gas well located near Blackpool, UK.¹⁵⁹ The earthquakes are attributed to the injection of

¹⁵¹ Jacobi, 2002

¹⁵² Isachsen and McKendree, 1977

¹⁵³ EarthSat, 1997

¹⁵⁴ Jacobi, 2002

¹⁵⁵ Fluhr and Terenzio, 1984

¹⁵⁶ Frohlich et al., 2011

¹⁵⁷ Frohlich et al., 2010

¹⁵⁸ Cysper and Davis, 1998

¹⁵⁹ de Pater and Baisch, 2011

HVHF fluids into a previously unknown fault. There is also evidence to suggest that magnitude 1.0 to 2.8 earthquakes in Garvin County, Oklahoma could have been caused by HVHF operations.¹⁶⁰

Deep injection wastewater disposal wells that are used in some HVHF operations for disposal of HVHF fluids returned to the surface have an even stronger link to induced seismicity. Several such cases are reported in the RDSGEIS, for example, the Dale Brine Field, New York¹⁶¹ (maximum magnitude 2.7); the Barnett Shale gas play near Dallas-Fort Worth, Texas¹⁶² (one magnitude 3.3 event, and many over M1.5), and the Fayetteville Shale gas play in Arkansas.¹⁶³

5.4.3 HVHF Confined to the Target Formation

HVHF operations attempt to limit fracturing to the target formation. The presence of effective geological barrier formations above and below the target formation is an important element of a successful gas play because it prevents gas released by HVHF from escaping and helps maintain pressure that directs the gas to the well bore for production. While this is the ideal case, microseismic monitoring of HVHF activities has shown that induced fractures can propagate into adjacent formations.¹⁶⁴ The RDSGEIS notes that ICF International observed that:

“fracture monitoring by these methods is not regularly used because of cost, but is commonly reserved for evaluating new techniques, determining the effectiveness of fracturing in newly developed areas, or calibrating hydraulic fracturing models.”

It is often not known how far induced fractures propagate into surrounding formations.¹⁶⁵

As discussed in Section 2.2.1, Engelder¹⁶⁶ notes that joint set J2 extends 500 feet to 4,000 feet into the formations above the Marcellus Shale, possibly indicating a gas halo that formed by natural hydraulic fracturing of the Marcellus during thermal maturation.

5.5 Adequacy of the Protections

The sole protection for the WOH NWI in the RDSGEIS is a 1,000-foot buffer zone from the well head to the tunnel. Drilling is not prohibited within the 1,000-foot buffer. Permits theoretically can be issued for locations *anywhere* within 1,000 feet of DEP WOH water supply tunnels pending a negative declaration of a site-specific SEQRA review. In addition, laterals in HVHF directionally-drilled wells may reach as much as a mile horizontally from the well head, so HVHF stimulation could occur directly under DEP WOH water supply tunnels even if the wellhead is thousands of feet outside the 1,000-foot buffer described in the RDSGEIS. Finally, the siting of deep injection

¹⁶⁰ Holland, 2011

¹⁶¹ Fletcher and Sykes, 1977

¹⁶² Frohlich et al., 2011

¹⁶³ Arkansas Oil and Gas Commission Order No. 180A-2-2011-7, August 2, 2011

¹⁶⁴ RDSGEIS, 2011

¹⁶⁵ RDSGEIS, 2011

¹⁶⁶ Engelder, 2008

wastewater disposal wells in the vicinity of the WOH NWI is possible pending a site specific SEQRA review.

The protections described above are not adequate to protect the WOH NWI. This statement is supported by evidence discussed in this section, summarized below:

- *Faults and brittle structures that cross DEP WOH Water Supply Tunnels have been shown to be more numerous than indicated in the RDSGEIS, and analysis of additional geophysical data could reveal even more faults and brittle structures;*
- *Recent case studies document that HVHF can induce earthquakes; and*
- *Earthquakes could cause tunnel damage.*

Section 6: Evaluation of the 2009 JV Recommendations

6.1 Introduction

Following the release of the DSGEIS in 2009, the JV issued documents that detail concerns regarding protections to the WOH Watershed and water supply infrastructure. These documents include:

- Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed, Rapid Impact Assessment Report, September, 2009 (RIA);
- Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed, Final Impact Assessment Report, December 22, 2009 (FIA); and
- Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed, Technical Memorandum: NYCDEP Infrastructure Risk for the West of Hudson (WOH)/Catskills Region of New York, *Draft*, November 3, 2009 (Infrastructure Risk Memo).

The RIA and FIA were released by DEP and were the basis for DEP's comments to NYSDEC on the DSGEIS. The RIA and FIA address several issues pertaining to HVHF operations, including surface impacts (chemical usage, spills, industrialization due to increase in trucking, and water withdrawals) and subsurface impacts (induced seismicity, loss of geologic isolation of Marcellus and deep brines through induced fracturing, discharge of contaminants into aquifers, tunnel damage), many of which are outside of immediate concerns to the WOH water supply tunnels. The Infrastructure Risk Memo more specifically addresses potential impacts to the NYC water supply infrastructure, but it is a draft document not released by DEP. In this section, we will examine *from a geophysical perspective* the recommendations set forth in 2009 by the JV to enhance tunnel protections and the evidence used to support their findings.

6.2 Overview of Recommendations

The primary recommendations of the JV with respect to protecting NYC water supply tunnels are as follows:

- Setbacks should be measured from the spacing unit, rather than the wellhead; and
- Setbacks from tunnels should be seven miles.

6.3 Justification for Recommendations

The main reasons provided by the JV to justify the recommendations for greater protective buffer to the NYC water supply tunnels are as follows:

- Presence of faults and other brittle structures within the vicinity of NYC water system tunnels that range from 1 to 7 seven miles in length;
- Analysis that shows that relatively low external differential pressures could cause failure of the unreinforced concrete tunnel linings;
- Transmissivity of fractures documented during tunnel construction demonstrated by methane and brine seeps;
- Potential for hydraulic fracturing fluids, deep formation waters, and methane to infiltrate tunnels; and
- Spatial extent and density of hydraulic fracturing activity expected as production ramps up.

For the remainder of this section, we will examine several aspects of this evidence, primarily that evidence pertaining to faults and the possibility of structural damage to the NYC water supply tunnels.

6.4 Evidence used by the JV to Justify Recommendations

6.4.1 Faults and Other Brittle Features

Evidence used to support a seven-mile buffer comes from research that shows the relative probability of faults of a given length occurring within the WOH Watershed region. Figure A-3 in the FIA shows a curve that plots the mapped lengths of brittle features documented by Isachsen and McKendree¹⁶⁷ and the probability that a given brittle feature will equal or exceed that length. Two curves are shown - one shows all brittle structures in the WOH Watershed and the other shows fourteen brittle features that appear to intersect the Water Supply Infrastructure. Using the data set of the fourteen brittle features in the vicinity of the tunnels, the probability plot shows that 10% of faults in the WOH tunnel vicinity exceed 7 miles in length, 50% exceed 3 miles in length, and all exceed 1,000 feet in length.

Faults and other brittle structural features, as well as brine and methane seeps were documented during construction of the tunnels¹⁶⁸ and Figure 2-7 of the FIA shows the locations of such features overlaid on a map of lineaments by Isachsen and McKendree. At several locations along the tunnel, near-vertical faults or fractures encountered during construction appear to be coincident with surface lineaments, suggesting the presence of faults that extend from the surface to at least the depth of the tunnel.

6.4.2 Tunnel Failure Analysis

The JV retained Jenny Engineering Corp to conduct an analysis of the external pressures needed to produce failure of the unreinforced concrete lining of the tunnels.¹⁶⁹ The Jenny Engineering analysis indicates that external differential pressures as low as 20 PSI could cause failure of the unreinforced concrete lining if unevenly loaded.

¹⁶⁷ Isachsen and McKendree, 1977

¹⁶⁸ Fluhr and Terenzio, 1984

¹⁶⁹ Jenny Engineering Corporation, 2009

6.5 Additional Evidence

In Sections 2, 3, and 4 of this Technical Memorandum, additional evidence is presented that was not considered for the 2009 publications by the JV, summarized below:

6.5.1 Faults and Brittle Structures

6.5.1.1 Evidence from Literature

The JV analysis of fractures in the vicinity of the WOH Watershed was conducted using the Isachsen and McKendree data set. More recently published data showing proposed faults and fractures exist, including an analysis of Landsat data by Earth Satellite Corporation (EarthSat) in 1997¹⁷⁰ and a study published by Jacobi in 2002.¹⁷¹ The analysis by EarthSat examined 1:250,000 and 1:500,000 scale satellite imagery mosaics to detect lineaments related to faults and fractures. Some of the lineaments detected by the EarthSat survey correspond to lineaments detected by Isachsen and McKendree, but additional previously unidentified lineaments were also detected. Several such previously undetected lineaments cross the Water Supply Tunnel alignments.

Jacobi mapped faults in New York State based on Landsat data, geophysical, and earthquake data.¹⁷² Based on lineaments detected in Landsat data, Jacobi extended the N-S trending Sprakers and Noses Faults, previously mapped in Montgomery and Schoharie Counties, southward through Delaware County into the northern portions of Sullivan and Ulster Counties. Jacobi's extension of Sprakers Fault crosses the East and West Delaware tunnels, and his extension of the Noses Fault is close to the tunnel alignments.

6.5.1.2 Orthoimagery Analysis

High resolution orthoimagery acquired by the NYCDEP in the WOH Watershed and along the East Delaware, West Delaware, and Neversink and Tunnels was examined for this project. Previously unknown projected possible faults that cross the tunnel alignments were interpreted, and the results of the analysis are shown in Figure 1. In addition, the approximate locations of the N-S trending faults interpreted by Jacobi are shown on Figure 1. The interpreted faults show good correspondence with faults and brittle features encountered during tunnel construction.¹⁷³

¹⁷⁰ EarthSat, 1997

¹⁷¹ Jacobi, 2002

¹⁷² Jacobi, 2002

¹⁷³ Fluhr and Terenzio, 1984

6.5.2 Earthquakes

Naturally occurring earthquakes in New York State have been monitored by the Lamont -Doherty Cooperative Seismic Network from 1970 to present. As discussed in Section 2.4, three small seismic events have been recorded in the vicinity of the WOH NWI, and one magnitude 4.0 earthquake was recorded in western Schoharie County north of the WOH Watershed. The fact that earthquakes, albeit too small to be felt or to cause damage at the surface, occurred in the vicinity of the WOH Watershed indicates that at least one seismically active fault could be present in the region.

6.5.3 Seismicity Induced by Hydraulic Fracturing

Section 3 of this document discusses in greater detail microseismicity induced by hydraulic fracturing. It had long been the NYSDEC's position that there was no conclusive evidence that hydraulic fracturing has caused an earthquake.^{174,175,176} Recently, however, seismic events of magnitudes 2.3 and 1.5, as well as numerous smaller events, have been conclusively linked to HVHF operations located near Blackpool, UK.¹⁷⁷ The earthquakes are attributed to the injection of hydraulic fracturing fluids into a previously unknown fault. There is also evidence to suggest that magnitude 1.0 to 2.8 earthquakes in Garvin County, Oklahoma¹⁷⁸ could have been caused by HVHF operations.

6.6 Adequacy of the Recommendations

6.6.1 Setbacks Measured from Edge of Spacing Unit

In Section 2, Hager-Richter provides analysis that indicates the presence of additional faults in the vicinity of the WOH NWI, and that at least one fault in the WOH Watershed region may be seismically active. In addition, there is now documented at least one case where HVHF has been conclusively attributed to induced earthquakes.¹⁷⁹ These findings highlight the need for caution in HVHF activity in the vicinity of critical structures such as the WOH NWI unreinforced concrete-lined tunnels.

The setbacks recommended by the JV are from the edge of the spacing unit. This setback would be especially important if, despite JV's recommendations for a seven-mile setback (see below), the 1,000-foot buffer is adopted, because the horizontal lateral of the well can extend several thousand feet laterally from the wellhead position. *Hager-Richter agrees with the JV recommendation that the minimum setback should be from the edge of the spacing unit so that no lateral will extend directly under the WOH NWI.*

¹⁷⁴ Frohlich et al, 2011

¹⁷⁵ Frohlich et al, 2010

¹⁷⁶ Cysper and Davis, 1998

¹⁷⁷ de Pater and Baisch, 2011

¹⁷⁸ Holland, 2011

¹⁷⁹ de Pater and Baisch, 2011

6.6.2 Recommended Setback of Seven Miles

The JV has recommended a seven-mile setback to drilling, measured from the tunnel to the edge of the spacing unit. The JV bases the seven-mile setback on an analysis showing that 10% of brittle structures that intersect the WOH water supply tunnels will equal or exceed 7 miles in length. The JV used a reasonable statistical model for the recommended seven-mile setback.

This Technical Memorandum documents additional faults and fractures in the vicinity of the WOH water supply tunnels and found evidence showing that, at least in the case of Blackpool, UK, earthquakes have been conclusively attributed to HVHF operations. Based on the evidence of faulting, the possible reactivation of faulting due to HVHF, and the unprecedented nature of HVHF activity under critical water supply tunnels for a large population, *Hager-Richter agrees with the assessment of the JV that a much greater protection than the 1,000-foot buffer afforded in the RDSGEIS is required to protect the WOH NWI*

Hager-Richter does not recommend a specific revised setback distance herein because 1) there are too many uncertainties about site specific subsurface geological and geophysical conditions in the vicinity of the WOH NWI, and 2) the condition of the unreinforced concrete-lined water supply tunnels is unknown. The need for extra caution in the vicinity of the WOH NWI is obvious, but what constitutes an acceptable level of risk of damage to the critical water supply infrastructure is more a matter of policy, not geophysics.

Hager-Richter does recommend that horizontal drilling and HVHF treatment not be permitted along any fault, known or detected, in the WOH NWI due to the low, but real possibility of reactivation of a fault that might experience sufficient slippage to damage the unreinforced concrete lining of the critical NYC water supply tunnels. Such faults should include all those mapped during construction of the tunnels as well as brittle structures, lineaments, and faults mapped by Isachsen and McKendree, EarthSat, Jacobi and Hager-Richter and shown on Figure 1, and all structures determined in site-specific testing.

There is not enough geophysical information available to recommend a specific setback distance from the infrastructure along a fault mapped in the infrastructure in which horizontal drilling and HVHF should be barred. If horizontal drilling and HVHF is proposed in the vicinity of one of the faults that cross the water supply tunnels, Hager-Richter recommends that detailed site characterization of the proposed drilling site and the area between that location and the WOH NWI be required to demonstrate that faults are not present and the results provided to NYSDEC and DEP prior to issuing a permit. Such site characterization should include determination of the local stresses, attenuation properties of bedrock, and detailed fault mapping in the target formation and in the interval between the target formation and the infrastructure. Geophysical technology is available and routinely used by the shale gas industry in the form of high resolution 2D and 3D seismic reflection methods to determine in advance of drilling whether faulting is present in the vicinity of a proposed drilling location and between that location and the WOH NWI. If drilling is approved, LWD methods and active microseismic monitoring should be required, and those results should also be provided to the NYSDEC and DEP. LWD methods can help detect unknown faulting, and active microseismic monitoring during HVHF treatment that can help constrain the effects of HVHF to minimize the possibility of reactivation of a fault and damage to the WOH NWI.

Section 7: Conclusions and Recommendations

Based on the review of existing geophysical data, we conclude:

- *The subsurface formations underlying and in the vicinity of the WOH NWI are much more complexly jointed and faulted than indicated in the RDSGEIS, and the joints and faults are not well characterized in the interval between the WOH NWI and the Marcellus Shale.*
- *Figure 4.13 of the RDSGEIS is not sufficient to characterize faulting in the vicinity of the WOH NWI.*
- *Faulting documented in the WOH NWI should be considered “known, significant, and mapped,” terminology used in the RDSGEIS, by virtue of its documented presence in critical infrastructure. The faults could extend to the depths of the Marcellus Shale.*
- *Seismicity data for the immediate vicinity of the WOH NWI are limited to three very small events, at least one of which could have been caused by human activity, but raise the possibility that one or more faults in the vicinity of the WOH NWI is seismically active.*

Based on an assessment of the effects of microseismicity associated with horizontal drilling and HVHF on the WOH NWI, we conclude:

- *The vibrations from individual and multiple microseismic events due to routine HVHF activities are not likely to damage the WOH NWI tunnels.*
- *Literature review of tunnel failures due to earthquakes show that tunnels can be damaged by seismic events with magnitudes less than 4 and that tunnels can be damaged by seismic events on faults located greater than 25 km from the tunnel.*
- *It is documented that thousands of shale gas wells have undergone HVHF treatment in the US without triggering earthquakes, but recently released research has shown that HVHF stimulation of a shale gas well triggered low magnitude earthquakes near Blackpool, UK and likely did so in Oklahoma in 2011. The Blackpool site is in a region of low seismicity and the fault was unknown prior to the drilling and HVHF stimulation. The recently released research raises the possibility, however small, that HVHF treatment of horizontal drill holes in the vicinity of the WOH NWI could induce one or more earthquakes that the unreinforced concrete lined water supply tunnels would not experience otherwise.*
- *Obtaining as much information as possible about the subsurface stress field is critical for engineering HVHF stimulation and in assessing the potential for induced seismicity in any area, but detailed site specific geophysical data for the WOH NWI region are not available. The absence of direct geophysical data from borehole logging and high resolution seismic reflection surveys, and the natural complexity in rock properties all contribute to the uncertainty in understanding the contemporary stress field and the possible presence of critically stressed faults in the vicinity of the WOH NWI.*

- Modeling an HVHF induced earthquake of the same maximum magnitude of 2.3 recorded at the Blackpool site in the UK indicates a movement of about 3/8 inch on a fault. *At this time, there is not enough known about the state of stress and faulting in the vicinity of the WOH NWI and details about the condition of the unreinforced concrete-lined tunnels of the WOH NWI to determine whether the tunnels would be damaged by an induced seismic event of the type modeled.*
- The Blackpool earthquakes and probably the Oklahoma earthquakes demonstrate that HVHF fluids can reach a nearby fault and can trigger a seismic event. *Therefore, the RDSGEIS statement that “the possibility of fluids injected during hydraulic fracturing the Marcellus or Utica Shales reaching a nearby fault and triggering a seismic event are remote for several reasons” is not consistent with recent evidence of HVHF-induced earthquakes.*
- Because the peak horizontal ground accelerations of earthquakes likely to be induced by HVHF are comparable to values determined in a probabilistic seismic hazard analysis of the DEP Catskill/Delaware dams, *we conclude that the potential risk to the dams is no greater than the risk due to natural earthquakes.*

We conclude that the protections in the RDSGEIS for the WOH NWI are not adequate to protect the NYC water supply tunnels because:

- Faults and brittle structures that cross NYC WOH Water Supply Tunnels have been shown to be more numerous than indicated in the RDSGEIS, and analysis of additional geophysical data could reveal even more faults and brittle structures.
- Recent case studies document that HVHF can induce earthquakes.
- Earthquakes could cause tunnel damage.

Based on review from a geophysical perspective of the 2009 JV recommendations, we conclude:

- *Hager-Richter agrees with the 2009 JV recommendation that the minimum setback should be from the edge of the spacing unit so that no HVHF lateral will extend under the WOH NWI.*
- *Hager-Richter agrees with the 2009 JV assessment that a much greater protection than the 1,000-foot buffer afforded in the RDSGEIS is required to protect the WOH NWI.*

Recommendations:

- *Hager-Richter recommends that horizontal drilling and HVHF treatment not be permitted along a fault mapped in the WOH NWI due to the low, but real possibility of reactivation of a fault that might experience sufficient slippage to damage the unreinforced concrete lining of the critical NYC water supply tunnels.*

- There is not enough geophysical information available to recommend a specific setback distance from the infrastructure along a fault mapped in the infrastructure in which horizontal drilling and HVHF should be barred. If horizontal drilling and HVHF is proposed in the vicinity of one of the faults that cross the water supply tunnels, Hager-Richter recommends that detailed site characterization of the proposed drilling site and the area between that location and the WOH NWI be required to demonstrate that faults are not present and the results provided to NYSDEC and DEP prior to issuing a permit.

Section 8: Limitations

This Technical Memorandum was prepared for the exclusive use of Hazen and Sawyer, P.C./Leggette, Brashears & Graham, Inc., Inc., A Joint Venture and the City of New York (collectively, Client). Hager-Richter Geoscience, Inc. (Hager-Richter) acknowledges Client's intention to make this Technical Memorandum available to the public. While members of the public may read and use this report, they do so at their own risk and without any liability to Hager-Richter in connection with the use of this Technical Memorandum or any information, documents, records, data, interpretations, advice or opinions given to Client in the performance of its work. The Technical Memorandum relates solely to the specific project for which Hager-Richter has been retained and shall not be used or relied upon by Client or any third party for any variation or extension of this project, any other project or any other purpose without the express written permission of Hager-Richter. Any unpermitted use by Client or any third party shall be at Client's or such third party's own risk and without any liability to Hager-Richter.

Hager-Richter has used reasonable care, skill, competence and judgment in the preparation of this Technical Memorandum consistent with professional standards for those providing similar services at the same time, in the same locale, and under like circumstances. Unless otherwise stated, the work performed by Hager-Richter should be understood to be exploratory and interpretational in character and any results, findings or recommendations contained in this Technical Memorandum or resulting from the work proposed may include decisions which are based on professional judgment and are not necessarily based solely on pure science or engineering. It should be noted that our conclusions might be modified if subsurface conditions were better delineated with additional subsurface exploration including, but not limited to, surface and borehole geophysical data, test pits, soil and rock borings with collection of soil, rock core, water samples, and laboratory testing.

Except as expressly provided in this limitations section, Hager-Richter makes no other representation or warranty of any kind whatsoever, oral or written, expressed or implied; and all implied warranties of merchantability and fitness for a particular purpose, are hereby disclaimed.

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NYCDEP WOH Non-Watershed Infrastructure Impact Evaluation

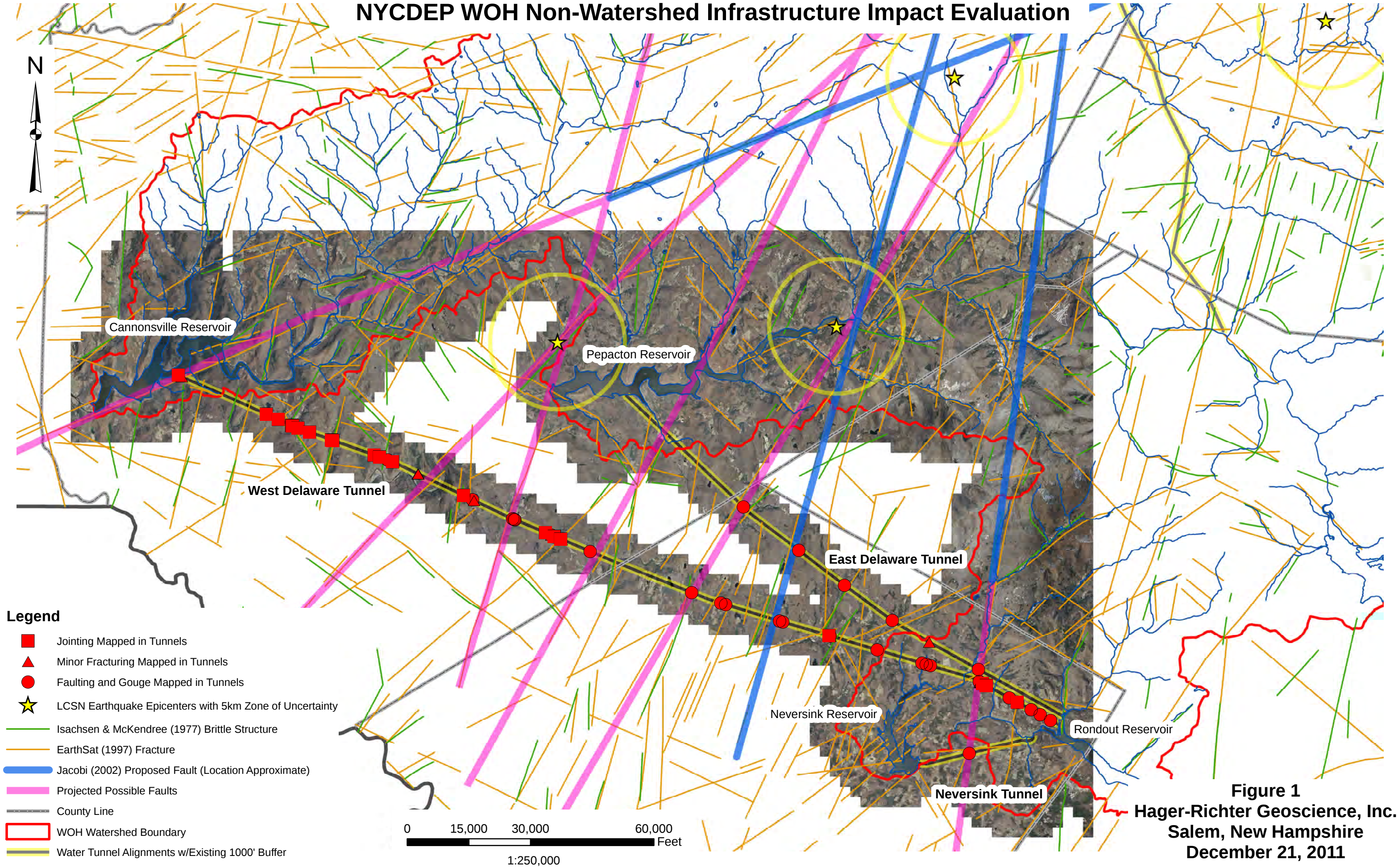


Figure 1
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