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## Report for the Delaware River Basin Commission Consolidated Administrative Hearing on Grandfathered Exploration Wells

To  
Delaware Riverkeeper Network  
and  
Damascus Citizens for Sustainability

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1) On behalf of the Delaware Riverkeeper, the Delaware Riverkeeper Network, and Damascus Citizens for Sustainability, I have reviewed numerous reports and much material that relates to the practice of developing gas wells in shales. Much of my focus relates to the Appalachian Basin that encompasses portions of New York State, Pennsylvania, New Jersey, and Delaware. While this testimony is oriented to exploration wells in Wayne County, PA and the broader Delaware River Basin, the concepts forwarded are applicable throughout the Appalachian Basin to areas overlying the Marcellus and Utica shales. In my professional opinion, vertical exploratory gas wells, as well as horizontal hydraulically fractured wells, create a high risk of contamination of the water resources of the Delaware River Basin. This risk exists not only at the time of drilling but also increases over time, because of a) the likelihood of failure of the well over time, b) the likelihood of eventual migration of toxic natural and drilling-related substances through extensive natural fractures that exist throughout the region, and c) the exacerbation of a) and b) above by natural or drilling-induced seismic activity. This report also documents significant natural seismic activity in and adjacent to the Delaware River Basin over time. Ground motions from even one significant earthquake, among many that occur over time, may catastrophically shear numerous gas well casings or, at the very least, may result in fracturing and loss of integrity of well casing cement designed to isolate freshwater aquifers from deep saline waters. As such, earthquakes may instantly destroy the integrity of hundreds of gas wells, thereby forever and irreparably compromising the hydrologic integrity of geologic formations that formerly protected freshwater aquifers. Restoration of contaminated freshwater aquifers is probably not possible, thus well failures from any single or combination of mechanisms is likely an irrevocable commitment of natural resources. These points will be discussed in greater detail below.

2) I offer this opinion based on my training as a geologist, hydrogeologist, and hydrologist with more than twenty-nine years of professional environmental experience, which includes work conducted for the New York State Attorney General's Office (Environmental Protection Bureau), Oak Ridge National Laboratory (Environmental Sciences Division), the New York City

Department of Environmental Protection, and as an independent environmental consultant as President of HydroQuest. My educational background and professional experience are more fully set forth in my Curriculum Vitae, attached as Addendum A, attached to my report. I have conducted detailed assessments of streams, wetlands, watersheds, and aquifers for professional characterizations, for clients, and as part of my own personal research. I have authored numerous reports and affidavits related to this work and have made presentations to judges and juries. In addition, I have published papers and led all-day field trips relating to this work at professional conferences.

### **Location and Bedrock Geology**

3) The Delaware River Basin encompasses portions of New York State, Pennsylvania, New Jersey, and Delaware. Figure 1 portrays this large watershed area. The exploratory wells that are the subject of this testimony lie in Wayne County, the furthest northeastern county of Pennsylvania. Immediately north, northeast, and east of Wayne County are three New York State counties: Broome, Delaware, and Sullivan respectively.

4) Geologically, Wayne County, PA is virtually indistinguishable from portions of Broome, Delaware, and Sullivan Counties. Figure 2 depicts similar geologic formations present in Broome, Delaware, Sullivan and other counties throughout New York State that lie in close proximity to Wayne County. Geologically, these units are composed of a series of sedimentary shales, siltstones, sandstones, and some conglomerates layered from the Honesdale Formation downward through and below the Marcellus Formation. These rock units were deposited under the same hydrologic conditions through the widespread area now recognized by geologists as the Catskill Delta. Before the sediments of these rock units were lithified into bedrock, they were shed northwesterly from the ancestral Acadian Mountains.

5) The subcrop of the Marcellus shale underlies portions of these New York State counties and all of Wayne County, PA. Portions of these counties, as well as portions of Schoharie, Greene, and Ulster counties in New York State, lie within the headwater region of the Delaware River Basin. In Figure 2, Wayne County, PA lies in a white area directly southwest of the boxed label titled: Cannonsville Reservoir Delaware R. headwaters.

6) As reflected in Figure 2, it is apparent that erosion has, in places, removed some of the uppermost bedrock units through glaciation and erosion. In places, Wayne County and nearby watershed areas have the same bedrock units exposed at the ground surface. Significantly, geologically and hydrologically, ground and surface water flow in Wayne County and surrounding counties behaves similarly – all potentially being vulnerable to gas field related contaminants from below and above.

7) The Marcellus and Utica shales extend under a large, multi-state, land area. The environmental risks associated with the installation of vertical exploratory wells and hydraulic fracturing are interstate in nature and must be fully evaluated in this manner - not solely state by state or watershed by watershed. The need to comprehensively evaluate and regulate hydrologic and hydrogeologic risks on a gas field basis is paramount.

## **Joints, -Faults, Methane Presence, and Blowouts**

8) Jacobi (2002) documented numerous joints and faults (collectively termed fractures) present throughout the headwaters of the Delaware River Basin, as well as elsewhere throughout portions of New York State overlying the Marcellus and Utica shales (Figure 3). While much of Jacobi's work did not extend into Pennsylvania, the density of these fractures clearly argues that similar joint sets and faults are present in neighboring Wayne County, PA and beyond. Reference to Figure 3 reveals the dominant NW, N-NW, NE, and E-NE fracture orientations. As seen below, these trends coincide with those throughout the broader Appalachian Basin.

9) Exploratory wells may target or have a high likelihood of penetrating vertical bedrock joints that have the potential of hydrologically connecting saline and freshwater horizons. Prominent joint orientations throughout the Appalachian Basin, inclusive of Wayne County Pennsylvania, are well documented by Evans (1994), Engelder et al. (2009), and Lash and Engelder (2009). Figure 4 depicts four figures from Engelder et al. (2009) and Lash and Engelder (2009) that illustrate dominant joint orientations throughout the Appalachian Basin. These geologists determined that most pervasive systematic joints hosted by Devonian black shale strike east-northeast ( $J_1$  joint set) with younger cross-fold joints striking northwest ( $J_2$  joint set). They concluded that *"[B]oth sets were driven exclusively by fluid pressure generated as a consequence of hydrocarbon-related maturation supplemented by subsequent tectonic compaction during the Alleghanian tectonic cycle. In the more deeply buried, proximal region of the Catskill Delta, joints of both sets cross-cut."* (Lash and Engelder, 2009). Figure 3 confirms this cross-cutting relationship in New York State counties immediately north, northeast, and east of Wayne County. Engelder et al. (2009) confirm that the more permeable  $J_1$  joint sets are found at depth in the Marcellus based on the presence of systematic  $J_1$  joints in Marcellus outcrops on either side of the deep central region of the Appalachian Basin, as well joint appearance in Formation MicroImager images of recent wells. Thus, two regional, well-integrated, perpendicular joint sets exist throughout Wayne County, PA. Exploratory and other wells have a high likelihood of intersecting these interconnected joint sets.

10) Vertical exploration wells, even in the absence of stimulation via hydraulic fracturing, pose similar environmental risks as do horizontal well completions. Natural fractures function as high-permeability gas pathways (Engelder et al., 2009). The greater the fracture interconnectivity, the greater the potential gas production. Recent drilling technology in the Marcellus Shale uses hydraulic fracturing to take advantage (i.e., maximize production) of the more densely spaced and more permeable E-NE oriented  $J_1$  joint sets by interconnecting them via horizontal drilling methods oriented perpendicular to  $J_1$  joints (i.e., N-NW and S-SE). Hydraulic fracture interconnection results in  $J_2$  joints draining to  $J_1$  joints and gas production wells. In the absence of hydraulic fracturing, vertical exploratory wells have been known to intersect high permeability gas-bearing fractures, sometimes with disastrous results. Engelder et al. (2009) document the presence of unhealed (i.e., methane-filled) joints at depth in the Marcellus shale and major blowouts that occurred when these unhealed joints were encountered (as cited from Bradley and Pepper, 1938 and Taylor, 2009). For example, Taylor (2009) discusses the 1940 Crandell Farm blowout near Independence, New York where massive uncontrolled gas flow occurred from joints intersected by an unstimulated vertical Marcellus well that lacked any evidence of faulting. Engelder et al. (2009) further discuss blowouts in the

Marcellus Shale after the Crandell Farm blowout:

*“Over the following half century, blowouts were a common consequence of drilling vertical wells penetrating the Marcellus. The low permeability of the Marcellus suggests that many, if not all, blowouts must have tapped a reservoir of interconnected natural fractures. In fact, blowouts were one of the major attractions drawing Range resources to Washington County, Pennsylvania, where Range started targeting the Marcellus gas shale during 2004 (W.A. Zagorski, personal communication).”*

11) Engelder et al. (2009) document that, even in the absence of stimulation, some gas wells that tap unhealed and well-interconnected joint sets at depth are excellent producers. Clearly, preserved unhealed joints are important to gas production because healed fractures and veins would otherwise serve as barriers to gas flow (Engelder et al., 2009). Thus, vertical exploration wells that intersect permeable, gas-rich, interconnected joint sets pose a potential hydraulic pathway (i.e., with a decreasing pressure gradient) for upward migration and release of methane, especially in the event of casing or grout failure or stemming from seismic activity – whether natural or induced at some point later in time by hydraulic fracturing. In the latter case, earthquake or micro-seismicity stemming from future hydraulic fracturing in the area may result in shearing of exploration well casing and the opening of inter-formational pathways. Beyond this, blowouts themselves may pose a means of catastrophically interconnecting brine-rich and freshwater geologic horizons. Therefore, vertical exploration wells bear many of the same potential adverse environmental impacts as hydraulically fractured horizontal wells.

12) Numerous joints in the Appalachian Basin, even in the absence of gas well installations, provide open, functioning, avenues for upward migration of methane. Gas-rich joints encountered by exploration well boreholes may interconnect and enhance preexisting joint pathways for methane, deep-seated saline water, radioactivity and, following development of horizontal gas wells, for contaminated LNAPL (Light Non-Aqueous Phase Liquids; e.g., chemicals with a density less than freshwater, such as benzene) fracture fluids to migrate to aquifers, reservoirs, lakes, rivers, streams, wells, and even homes.

13) Importantly, Figure 3 of New York State counties north, northeast, and east of Wayne County, PA provides a conservative approximation of the actual number of joints and faults present throughout the area. In establishing a relationship between seismicity and faults, Jacobi (2002) examined Fracture Intensification Domains (FIDs: closely spaced fractures commonly with a frequency greater than 2/m and with a fracture frequency an order of magnitude greater than in the region surrounding the FID), E97 lineaments (Fig. 3), topographic lineaments, gradients in gravity and magnetic data, seismic reflections profiles, and well logs. Jacobi states:

*“In interbedded shales and thin sandstones in NYS, fractures within the FID that parallel the FID characteristically have a fracture frequency greater than 2/m, and commonly the frequency is an order of magnitude greater than in the region surrounding the FID.”*

14) Jacobi makes a case for repeated reactivation along faults in the Appalachian Basin. Furthermore, and importantly, Jacobi addresses his and Fountain’s identification of FIDs based on soil gas anomalies over open fractures:

*“Certain sets of FIDs are marked by soil gas anomalies commonly less than 50 m wide (Jacobi and Fountain, 1993, 1996; Fountain and Jacobi, 2000). In NYS, the background methane gas content in soil is on the order of 4 ppm, but over open fractures in NYS, the soil gas content increases to 40-1000+ ppm.”*

The fact that Jacobi and Fountain have successfully identified and measured methane seepage from fractures that most likely extend downward to gas producing shales shows that open vertical pathways already exist, confirming the risk of increasing gas excursions as a result of exploratory boreholes penetrating joints or, later in time, as horizontal wells are hydraulically fractured. Clearly, Jacobi and Fountain’s work suggests that opening and expanding fractures that now naturally release methane from gas-rich shales will provide even greater gas and contaminant migration pathways if later interconnected and widened via hydraulic fracturing. As with environmental concerns attendant to completing hydrofracked horizontal gas wells, installing vertical exploratory boreholes into gas-rich joint sets should not occur until after full environmental review.

### **Earthquakes, Seismicity, and Risk of Casing Shearing**

15) The installation of exploratory wells that open borehole or nearby joint pathways between formerly separated geologic horizons pose an environmental risk, particularly because the area is seismically active. Ground motion associated with seismic activity has the real potential of instantly shearing multiple well casings, degrading cement grout designed to isolate geologic horizons, and thereby opening vertical joint and borehole vectors between formerly separated geologic horizons. Numerous earthquakes have occurred in Pennsylvania, New York, and adjacent states (see Addendum B and Addendum C), pointing out that the region of the exploratory wells is seismically active. Figure 5 depicts historical earthquake epicenters, documenting that significant portions of the Appalachian Basin are seismically active. Figure 6 portrays USGS seismic hazard maps for Pennsylvania, New York, Delaware, and New Jersey. The Wayne County, PA area shows a peak horizontal ground acceleration of some 6-8% g with a 2% probability of exceedance in 50 years (i.e., earthquake ground motions that have a common given probability of being exceeded in 50 years). The %g relates to the acceleration due to gravity. It is a measure of ground motion that decreases the farther one is from an earthquake epicenter. A 6-8%g roughly correlates with a Modified Mercalli Intensity of VI. This intensity of an earthquake is likely to be felt by everyone, may result in movement of heavy furniture, and may damage house plaster and chimneys (DCNR, 2006). While damage on the ground surface is slight, it is likely that damage to casing grout and possibly well casings may occur – potentially compromising the integrity and physical isolation of different bedrock horizons.

16) Seismic activity in Pennsylvania and nearby states may result in significant ground motions that may compromise the integrity of well grout and casing. This, in turn, may result in interformational mixing of groundwater along exploratory well boreholes or adjacent joints. Earthquakes have occurred in Pennsylvania and elsewhere (DCNR, 2006). One of the largest earthquakes, of unknown magnitude, had an epicenter near Attica, NY and is reported to have cracked walls in Sayre, PA in 1929. Sayre is located in Bradford County, only some 50 miles

from Wayne County. Another nearby New York State earthquake, with a magnitude of 5.5, occurred in New York City in 1884 (only about eighty miles from Wayne County, PA), again documenting that the region is seismically active.

17) Numerous earthquakes have occurred in Pennsylvania, many in recent time, with the largest recorded in 1998 with a magnitude of 5.2. Some of those reasonably close to Wayne County include Berks County (to magnitude 4.0 and 4.6 in 1994), Bucks County (to 2.5), Lancaster County (to 4.4), Lehigh County (to 3.3), Monroe County (immediately south of Wayne County; 3.4, epicenter may have been in NJ), and Montgomery County (3.5). While these earthquakes did not produce substantial damage, there is a reasonable probability that higher magnitude earthquakes, with related damage, may occur. DCNR (2006) details this real possibility:

*“Earthquakes having magnitudes greater than 5 can occur in Pennsylvania, as demonstrated by the earthquake of September 25, 1998 (Armbruster and others, 1998) (Table 2, Crawford County). Southeastern Pennsylvania, the state’s most seismically active region, is not known to have experienced an earthquake with magnitude greater than 4.7, but the historical record goes back only about 200 years. No obvious reason exists to conclude that an earthquake of magnitude between 5 and 6 could not occur there also. An earthquake with magnitude greater than 6 is much less likely, but the fact that such large earthquakes have occurred elsewhere in the East means that this possibility cannot be ruled out entirely for Pennsylvania. ... The possibility that a magnitude 7 earthquake could occur having an epicenter near New York City cannot be completely discounted, and such an earthquake could produce significant damage (intensity VIII) in eastern Pennsylvania. ... A large local earthquake, one with magnitude greater than 6, though unlikely, is not impossible.”*

18) Earthquakes of these magnitudes in Pennsylvania have the real potential of resulting in sufficient ground motion to shear well casings and degrade the integrity of grout designed to physically separate different geologic and hydrologic horizons. For example, earthquakes of magnitude 5.0 to 5.9 on the Richter or moment magnitude scales can cause major damage to poorly constructed buildings. Wikipedia provides an approximate energy equivalent in terms of TNT explosive force for a 5.0 Richter magnitude earthquake as being equivalent to the seismic yield of the Nagasaki atomic bomb. Clearly, the decision to permit installation of exploratory wells, or horizontal wells, should be based on a comprehensive analysis of all environmental risks. It should be noted that the risk to grout and casing integrity exists both from natural earthquake activity and, in the case of hydraulically fractured horizontal wells, from microearthquakes stemming from fluid-induced seismicity (Bame and Fehler, 1986; LI, 1996; Feng and Lees, 1998; Horálek et al., 2009; Shapiro and Dinske, 2009). Therefore, the potential impacts of seismicity, whether from natural or man-induced activities, should be extensively analyzed prior to any deep drilling efforts. Because portions of Pennsylvania are seismically active, a real risk exists that earthquakes might instantly and catastrophically degrade casing grout integrity and shear multiple well casings, resulting in the commingling of formation fluids and release of methane. Unlike the recent British Petroleum disaster in the Gulf of Mexico, once the integrity of bedrock formations is breached, it will not be possible to restore degraded freshwater aquifers.

19) As an example of active seismicity in the Appalachian Basin, Jacobi and Smith (2002) document the epicenters of three seismic events in eastern Otsego County, New York. These seismic events indicate that earth movement occurs from great depth along faults upward to aquifers and near the ground surface. The great lateral extent of these faults, and their visually observable connectivity with other faults, confirms that the process of gas drilling activities, which may interconnect naturally occurring faults and fractures, has a great and very real potential of causing contaminants to migrate to aquifers and surface water from localized zones across and beyond county and watershed boundaries.

### **Grout and Casing Failure**

20) The high risk of compromising the integrity of the physical separation of freshwater aquifers from deeper saline water-bearing bedrock formations may be compounded as a result of well grout and casing failures that occur A) as a result of poor well construction (e.g., as in the BP well failure), B) due to mechanisms including cement shrinkage, or C) due to differences in downhole bedrock conditions (e.g., pressure differentials). Zhou et al. (2010) point out that casing pipes in well construction may suddenly buckle inward as their inside and outside hydrostatic pressure difference increases. Dusseault et al. (2000) document the many reasons why oil and gas wells leak, thus providing important supportive scientific rationale as to why both vertical exploratory wells and horizontal gas wells should not be permitted in advance of extensive environmental risk characterization:

*“Oil and gas wells can develop gas leaks along the casing years after production has ceased and the well has been plugged and abandoned (P&A). Explanatory mechanisms include channeling, poor cake removal, shrinkage, and high cement permeability. The reason is probably cement shrinkage that leads to circumferential fractures that are propagated upward by the slow accumulation of gas under pressure behind the casing.*

*The consequences of cement shrinkage are non-trivial: in North America, there are literally tens of thousands of abandoned, inactive, or active oil and gas wells, including gas storage wells, that currently leak gas to surface. Much of this enters the atmosphere directly, contributing slightly to greenhouse effects. Some of the gas enters shallow aquifers, where traces of sulfurous compounds can render the water non-potable, or where the methane itself can generate unpleasant effects such as gas locking of household wells, or gas entering household systems to come out when taps are turned on.”*

21) Dusseault et al. (2000) detail the underlying causes behind tens of thousands of grout failures in North America that likely compromise environmental security and zonal isolation while leading to contamination of freshwater aquifers. They conclude that:

- Surface casings have little effect on gas migration;
- Water-cement slurries generally placed at low densities will shrink and will be influenced by elevated pressures and temperatures encountered at depth;

- While cement is in an almost liquid, early-set state, massive shrinkage can occur by water expulsion, resulting in shrinkage of the annular cement sheath;
- Portland cements continue to shrink after setting and during hardening;
- Other processes can lead to cement shrinkage. High salt content formation brines and salt beds lead to osmotic dewatering of typical cement slurries during setting and hardening, resulting in substantial shrinkage;
- Dissolved gas, high curing temperatures, and early (flash) set may also lead to shrinkage;
- Initiation and growth of a circumferential fracture (“micro-annulus”) at the casing-rock interface will not be substantially impeded because cement shrinks;
- Circumferential fractures develop and gas leakage typically increase over time;
- Wells that experience several pressure cycles are more likely to develop circumferential fractures;
- Circumferential fractures propagate vertically upward because of the imbalance between the pressure gradient in the fracture and the stress gradient in the rock;
- Free gas will serve to further degrade the casing-grout-rock interface, increase gas flow into circumferential fractures, and may lead to continuous gas leakage;
- In turn, differences in pressure favor driving gas, and pressurized fluids present at depth, upward and outward from circumferential fractures back into bedrock formations (including those present in freshwater aquifers) where the pore pressure is less. Over time, the excess pressure is large enough to fracture even excellent cement bonds and force flow outward into surrounding strata;
- Methane from leaking wells into freshwater aquifers is unlikely to attenuate, and the concentration of the gases in shallow aquifers will increase with time;
- Loss of this zonal seal can have negative effects, such as pressurizing higher strata, or leakage of brines and formation fluids into shallower strata causing contamination; and
- Despite our best efforts, the vagaries of nature and human factors will always contribute to grout failures.

22) As detailed above by Dusseault et al. (2000), gas leakage up circumferential fractures at the cement-bedrock interface may also enter and degrade freshwater aquifers. In fact, the greatest risk of this occurring is in vertical wells, not in deep horizontal wells that have not been hydraulically fractured (Dusseault et al., 2000). Thus, unfracked vertical exploratory wells pose a greater environmental risk than do deep, unfracked, horizontal boreholes. When the above issues are considered within the broader context of documented regional seismicity, the real threat to the long-term integrity of our freshwater aquifers and quality of our surface waters is obvious.

### **Contamination of Freshwater Aquifers and Loss of Aquifer Integrity**

23) Contamination of freshwater aquifers via the mechanisms detailed above by Dusseault et al. (2000) (i.e., methane entering formations from leaking circumferential fractures) is likely to be far greater than more limited contamination proximal to well heads. Freshwater aquifers in



Wayne County, PA extend to at least 665 feet, as observed at the Matoushek #1 well (Stiles, 2010). Permitting the installation of vertical exploration wells needs to be considered in the broader environmental setting where these wells may ultimately be completed as hydrofracked horizontal production wells. Should natural ground motion from earthquakes (and possibly from seismically induced earthquakes from future hydrofracked wells) occur, it is likely that alternate groundwater flow paths will develop. These flow paths will then provide avenues for migration of gas well related contaminants, particularly low density or gaseous ones. Pre-existing joint sets that are already open to gas-rich shales (Jacobi, 2002) will provide pathways and release avenues for methane and any Light Non-Aqueous Phase Liquids that may be present. In this way, vertical fractures extending into overlying bedrock formations may result in the disruption and alteration of natural groundwater flow.

24) Understanding the cumulative impacts of natural gas drilling in the Delaware River Watershed is essential in order to determine how this activity should be regulated. By way of analogy, using a somewhat different but worst case example, solution mining in Tully Valley, New York, demonstrates how alteration of a previously isolated and intact freshwater aquifer was compromised via anthropogenic activities. While not physically observable on the ground surface, the adverse environmental impacts of gas production throughout large portions of the Appalachian Basin, may have much broader and far reaching impacts. The Tully Valley example described below demonstrates the nature and consequences of disrupting a previously intact groundwater flow regime. This analogy is especially applicable to adverse environmental impacts likely to occur with additional well drilling.

25) Deep solution mining of salt beds in Tully Valley, conducted under NYSDEC mining permits, regulation, and oversight has resulted in slow and catastrophic collapse of portions of Tully Valley from depths of 1,700 feet (518 m) to the ground surface. Rubin et al. (1992) document the structural failure of portions of the valley overlying and adjacent to brine cavities where salt was removed. The resulting settlement area is in excess of 550 hectares (~1,360 acres; 2.1 mi<sup>2</sup>). It continues to expand outward. Upward fracture propagation eventually resulted in open permeable pathways where fresh aquifer and infiltrating meteoric water began to recharge formerly isolated groundwater flow regimes, thereby establishing new deep flow routes that now result in connate, saline, and turbid water discharge to the ground surface, and Onondaga Creek (see Figure 7).

26) As illustrated in the Tully Valley example, once even a few significant fracture interconnections (i.e., planer, laterally extensive, and potentially interconnected with Fracture Intensification Domains) are established between target shale beds and the ground surface, naturally isolated groundwater flow systems then become accessible for commingling of formation waters, for transmission of contaminants, for the unnatural and increased recharge of deeper formations, and for the establishment of new groundwater flow routes. Much as methane can be released upward to lower pressure formations from exploration wells, so will LNAPLs rise upwards along fault and fracture pathways as more wells are drilled and developed, thereby broadly contaminating freshwater aquifers. Then, as new groundwater circulation pathways develop in response to repeated hydro-fracturing and newly available freshwater hydraulic/pressure heads, more and more commingling of freshwater and contaminant-laden, saline, water is likely. Thus, extensive natural fractures present throughout the Delaware River

Basin and broader Appalachian Basin may provide vectors for new interconnected groundwater circulation pathways.

27) With time, methane (and hydro-fracturing chemicals as gas production is permitted) will move with groundwater flow, down valley, toward zones of lower hydraulic head, particularly valley bottoms, major streams, and principal aquifers. Areas with higher groundwater flow velocities are likely to develop groundwater circulation patterns along Fracture Intensification Domains (i.e., high permeability pathways), especially where hydro-fracturing has opened elongate fracture pathways that have high hydraulic gradients between watershed uplands and valleys. To a large degree, these new circulation pathways will resemble those illustrated in the Figure 7 Tully Valley example – albeit fracture aperture width may be narrower and associated catastrophic collapse less likely.

28) While the focus of this testimony does not directly extend to horizontally hydraulically fractured gas production wells, it is not prudent to ignore the overall physical setting within which exploration well installations may ultimately fit. Since it has been shown above that many of the environmental risks normally attributed only to horizontal gas wells directly relate to unfracked vertical exploration wells (e.g., seismic risk, grout shrinkage, vertical flow pathways into freshwater formations), it is prudent to at least cursorily review broader gas production based environmental considerations. While gas field fracture aperture may be narrower than the disrupted Tully Valley example, it is important to recognize that the hydraulic transmissivity of fractures increases by the cube of the effective fracture width, thereby pointing out the likely increased risk associated with repeated hydro-fracturing. The combination of excessive pressure associated with hydro-fracturing and lubricated fault planes may lead to increased faulting and seismicity, followed by increased groundwater circulation between formerly isolated hydrologic horizons. Northrup (2010), for example, references a hydro-fracturing induced earthquake in Cleburne, Texas – the likely tip of the iceberg. Once these new groundwater circulation pathways are established, it will be impossible to restore the integrity of adversely impacted freshwater groundwater flow systems, contaminant migration and dispersal will expand, and plugging and abandonment procedures of gas production wells will have little impact on retarding water quality degradation throughout irreparably compromised aquifer systems.

29) Cumulative impact studies must address potential adverse environmental impacts associated with both exploratory wells and the overall long-term plan for the installation of hundreds or thousands of horizontal hydraulically fractured wells throughout the Delaware River Basin. Naturally occurring excursion of methane gas via faults and fractures has long been recognized. Recent studies are now beginning to confirm that methane, drilling chemicals, and hydro-fracking chemicals are migrating upward along hydro-fractured fracture pathways to freshwater aquifers and homeowner water supplies. For example, Lustgarten (2009) references scientific work conducted on methane gas excursions in Garfield County, Colorado where a three-year study used sophisticated scientific techniques to match methane from water to a deep gas-rich bedrock layer stating:

*“The Garfield County report is significant because it is among the first to broadly analyze the ability of methane and other contaminants to migrate underground in drilling areas, and to find that such contamination was in fact occurring. It examined more than*

*700 methane samples from 292 locations and found that methane, as well as wastewater from the drilling, was making its way into drinking water not as a result of a single accident but on a broader basis. As the number of gas wells in the area increased from 200 to 1,300 in this decade, methane levels in nearby water wells increased too. The study found that natural faults and fractures exist in underground formations in Colorado, and that it may be possible for contaminants to travel through them. Conditions that could be responsible include vertical upward flow along natural open-fracture pathways or pathways such as well-bores or hydraulically-opened fractures ...”*

30) What we are just beginning to understand is the fact that repeated fracturing at each well will further amplify all of these risks. Reaping maximum gas production from horizontal gas wells commonly requires repeated hydro-fracturing of wells (see discussion by Northrop, 2010). With each successive hydro-fracturing event, more toxic contaminants are introduced into subsurface formations, including those already aggravated and potentially opened in the first fracturing cycle. In addition, as gas companies expand their operations, they may turn to the new, more effective, multilateral drilling technology to selectively tap multiple target zones in adjacent areas. This will necessarily result in multiple wellheads and multiple fracturing operations in close proximity. Through these processes, it is highly likely that new, previously unconnected, fractures will be integrated into the area influenced by each production well.

31) David Kargbo et al. (2010), U.S. EPA Region III, recently cautioned about the particular challenges still unresolved about drilling in tight shale formations:

*“The control of well bore trajectory and placement of casing become increasingly difficult with depth...At the Marcellus Shale, temperatures of 35-51°C (120-150°F) can be encountered at depth and formation fluid pressures can reach 410 bar (6000 psi) (8). This can accelerate the impact of saturated brines and acid gases on drilling at greater depths. In addition, the effect of higher temperature on cement setting behavior, poor mud displacement and lost circulation with depth makes cementing the deep exploration and production wells in the Marcellus Shale quite challenging. For example following a recent report by residents of Dimock, PA, of natural gas in their water supplies, inspectors from the Pennsylvania Department of Environment Protection (PADEP) discovered that the casings on some gas wells drilled by Cabot Oil & Gas were improperly cemented, potentially allowing contamination to occur....During drilling into the tight Marcellus Shale, there is a slight risk of hitting permeable gas reservoirs at all levels. This may cause shallow gas blowouts and underground blowouts between subsurface intervals. Other geo-hazards that may pose challenges to drillers in the Marcellus Shale include: (1) disruption and alteration of subsurface hydrological conditions including the disturbance and destruction of aquifers, (2) severe ground subsidence because of extraction, drilling, and unexpected subterranean conditions, and (3) triggering of small scale earthquakes.”*

32) With each additional well and well activity, all of the “challenges” noted by Kargbo, Wilhelm, and Campbell of necessity multiply and increase. See also the BP internal report reported September 9, 2010, attributing fault for the 2010 Deepwater Horizon oil rig explosion to

unexpected cementing problems at pressures less than those of the average shale gas frack. Studies have not yet been done regarding the effect of depth and pressure on casing failure rates in tight shale formations nor on the repeated fracturing re-pressurization under such temperature and depth conditions on cement casings and joints. Nor have studies or plans been developed for remedial action should the casings and joints fail at extreme depth.

33) Risks of casing failure are further compounded by the frequency (or spacing) of casing couplings which may be on the order of every 100 feet or less. Zhou et al. (2010) assessed casing pipes in oil well construction and the risk that they may suddenly buckle inward as their inside and outside hydrostatic pressure difference increases. They point out the importance of measuring the stress state of casing pipe, complete with real-time monitoring and state-of-the-art warning system installations. Consideration should be given to evaluating cost-effective and reliable sensing technologies and installation techniques for long-term monitoring and evaluation of casing pipe before issuing gas well related regulations. Most deeply buried casings are difficult to repair or replace and, as such, can lead to aquifer contamination. Even a small percent casing or grout failure can be effectively irreparable at deep depths and irreparably harm ground and surface water sources.

34) Repeated hydraulic fracturing may activate pre-existing faults or induce shifting or settlement along lubricated fractures. Parts of Pennsylvania and New York State within and near the Delaware River Basin are seismically active. Excessive lubrication of faults and fractures with highly pressurized hydraulic fracturing fluids, bolstered by repeated hydrofracturing episodes, may result in fault activation and bedrock settlement. This, in turn, may result in catastrophic shearing of production well boreholes and casing strings even in the absence of natural seismic activity. Pre-existing old and poorly abandoned oil and gas wells may also provide additional contaminant migration pathways. Unlike the British Petroleum well that was finally plugged, once the structure of the bedrock has been compromised by faulting and/or hydraulic expansion of joints, and formation waters have commingled, aquifer restoration will not be possible.

35) The risk of ground collapse as a result of repeated fracturing cycles should also be studied prior to issuing regulations. “*Severe ground subsidence*” may occur “*because of extraction, drilling, and unexpected subterranean conditions*”, as may “*disruption and alteration of subsurface hydrological conditions including the disturbance and destruction of aquifers*” (Kargbo et al., 2010).

36) Homeowner wells do not need to be near gas production wells to be adversely impacted from the upward migration of methane gas and Light Non-Aqueous Phase Liquid contaminants from gas-rich shales. Neither discussion of known fracture frequency nor existing maps depicting massive fracturing throughout the Delaware River Basin appear to have been incorporated into the well permitting review process. As such, many of the real risks attendant to vertical exploratory well installations, or future horizontal hydraulic fracturing of gas-rich shale beds, have not been addressed. As some vertical fractures are widened and opened via hydrofracturing, they will and most probably have already, in some cases, provided a hydraulic avenue where methane is released upward into and throughout these well-integrated Fracture Intensification Domains. Thus, fractures enlarged by hydrofracturing will provide lower

pressure gas release points or routes. Once vertical and lateral fracture pathways are open, even a limited number, natural gas and LNAPLs will migrate extensively throughout formerly isolated upper bedrock and freshwater aquifer groundwater flow systems. As methane is released upward along vertical borehole pathways, and along future hydrofractured boreholes and their interconnected fractures, homeowner wells will provide a final open fracture and cased pathway to the ground surface from methane contaminated aquifers. Because horizontal components of gas wells extend may thousands of feet and may intersect numerous planar vertical pathways, large-scale aquifer degradation is possible. Initially, aquifer degradation can be expected above and adjacent to boreholes with poor grout seals. With time and successive hydrofracturing episodes conducted in individual wells, methane and LNAPLs that are released upward through fault planes and related fractures will widely contaminate freshwater aquifers and surface water receptors.

37) Some of the contaminated groundwater in areas now undergoing hydraulic fracturing is far removed from gas production wellheads, thus strongly indicating that groundwater contamination is already occurring along vertical fault and fracture pathways, distant from potential poor wellhead grout jobs or casing failures. This topic is discussed here because understanding the cumulative impacts of natural gas drilling in the Delaware River Watershed is essential in order to determine how this activity should be regulated. Fractures extend from gas-rich shales to the ground surface and naturally leak methane gas. Repeated hydraulic fracturing is likely to exacerbate this situation. Repeated hydraulic fracturing within numerous individual wells will serve to expand and extend these existing fractures through freshwater aquifers. This will increase upward migration of methane to aquifers, streams, homes, and wellheads. Dimock, Pennsylvania provides an excellent case in point.

38) It is likely that contaminant dispersal along fault, joint, and fracture pathways will be the more common mechanism whereby natural gas and LNAPL excursions find their way into aquifers, homeowner homes, well houses, and streams – not solely via pathways stemming from poor casing grouting. This mechanism also explains why many of the gas contamination incidents reported to date are far removed from individual gas production wellheads (e.g., up to 1,300 feet in the Dimock, PA area; COP 2009). This contaminant dispersal mechanism also strongly accents why gas companies would much prefer to admit that poor or failed casings or poor grout integrity is the root cause of gas excursion problems. Certainly, in the gas industry, it is far preferable to invoke any gas leak mechanism other than that of widespread, uncontrolled, and undocumented upward and lateral migration of formerly isolated methane gas into and through freshwater aquifers.

39) As in the Tully Valley example above, the loss of natural geologic and hydrologic integrity throughout formerly isolated geologic formations poses an enormous threat to the existing and future way of life in planned gas exploitation areas. However, the disruption of the geologic strata presented in the Tully Valley Figure 7, while having wider fracture apertures and relatively great vertical offset of geologic beds, has occurred in an area far smaller in areal extent than what is planned extensively throughout the Delaware River Basin and much of the Appalachian Basin. Gas excursions are likely to occur throughout the Appalachian Basin, wherever there are mapped and as yet undocumented fractures. Because of the physical nature of existing fractures systems, these excursions, even a few in an area, are likely to degrade freshwater aquifers such that

existing and new homeowner well installations will be degraded.

40) Because permitting of vertical exploration wells may result in numerous adverse environmental impacts (discussed above), it is important to fully consider the broader gas field development picture and related environmental impacts. Radioactive radium present in the Marcellus may also be mobilized in fluids and thus become available for transport in the groundwater flow system. This appears to be particularly true of uranium that University of Buffalo researchers recently determined is released during the hydraulic fracturing process (presented at a GSA meeting on Nov. 2, 2010). Tracy Bank and her colleagues determined that hydrofracking forces toxic uranium into a soluble phase and mobilizes it, along with chemically bound hydrocarbons, thereby making it available for groundwater transport. In addition, uranium tainted flow back water poses the risk of contaminating streams, wetlands, and ecosystems.

41) Fracking contaminants, once mobilized vertically along fault planes and joints, especially under pressurized conditions, can reach freshwater aquifers. Even if all fracking fluids were composed of non-toxic chemicals, the risk of interconnecting deep saline-bearing formations (i.e., connate water) and/or radioactive fluids with freshwater aquifers is great. Any commingling of deep-seated waters, with or without hazardous fracking fluids is unacceptable. Documented gas excursions near existing gas fields demonstrate that vertical pathways are open. If gas can migrate to the surface, it is highly likely that hydrocarbon and contaminant-rich Light Non-Aqueous Phase Liquids will also reach aquifers and surface water resources. These contaminants may then also migrate to down gradient wells, principal aquifers, and waterways.

42) Artificially enlarged and expanded hydrofracked fractures may provide vertical pathways for light, low density, drilling fluid chemicals and radon. Some fracking related contaminants will migrate upwards via fractures into freshwater aquifers - particularly Light Non Aqueous Phase Liquids (i.e., less dense hydrocarbons) inclusive of benzene, a known carcinogen. In addition, increased upward migration of radon is likely to occur. The pathways are already there and functioning, waiting to be further expanded and laced with toxic chemicals.

43) There is a growing catalog of hydro-fracking related accidents in other gas-field plays (see e.g., Hazen and Sawyer, 2009). Accidental spills of fracking fluids and flow-back water has the potential of contaminating ground and surface water. Similarly, lateral and upward migration of hydro-fracturing chemicals pose a real risk to Delaware River Basin aquifers, especially to moderate and high yield unconfined aquifers situated in stream valleys that receive their base flow recharge from up-gradient groundwater aquifers.

44) Excursion of drilling fluids and produced fluids from breached flow-back wastewater containment structures, whether via rupture, leakage, or overflow poses a real threat to surface water quality. Overland flow of flow back fluid chemicals to streams, ponds, wetlands, and waterways poses an immediate water quality and ecosystem concern that should be fully evaluated prior to issuance of draft regulations.

45) In the broader context of fully examining all potential adverse environmental impacts, it is

necessary to not only look at impacts associated with vertical exploration wells, but also planned future horizontal hydrofracked wells. Excursion of frack fluids from breached flow-back wastewater containment structures, whether via rupture, leakage, or overflow, poses a real threat to groundwater quality. Slow infiltration of frack fluid chemicals to groundwater and its potential degradation need to be fully addressed prior to issuance of draft regulations.

46) Poor or failing exploratory and production well construction (e.g., poor grouting, corroded casing) may provide vertical pathways for contaminant excursions from deep shale beds upward into freshwater aquifers. While this has already been documented, increased gas well installations will also increase the number of failed wells and resultant contaminant migration. Apparently, at this time, gas field contaminant excursions are not being treated as outward expanding contaminant plumes that warrant expensive, full-scale, hydrogeologic characterization, groundwater clean-up, and remedial action. The importance of this must be underscored because aquifer restoration on a gas field scale, even if cost were not an issue, may not be possible.

### **Endangered Species**

47) Methane that is released up vertical annular pathways between outer casing walls and bedrock formations almost certainly enters freshwater aquifers. The mechanisms involved are detailed by Dusseault et al. (2000) and pose a risk of groundwater contamination stemming from vertical exploration wells. As methane enters and accumulates in freshwater aquifers, it will move down gradient of its initial release avenues until an open release pathway is encountered (e.g., open joints). A risk that requires further research is that to Dwarf Wedge Mussels and other species present in streamways of the Delaware River Basin. Should methane or other gas field contaminants (e.g., benzene, LNAPLs) bubble up and be released into surface streams, they may compromise surface water quality and jeopardize the survival of an endangered species.

48) Excursions of gas field related contaminants may lead to degradation or loss of endangered and other species. Potential commingling of deep connate waters, hydrofracking fluids, methane, and freshwater aquifers, as a result of disrupted bedrock strata, may lead to new, altered, groundwater flow regimes. Altered flow regimes may, in turn, result in the formation of new aquifer discharge locations that effuse methane and other contaminants to streams, springs, wetlands, or other locations. The potential exists for such contaminants to degrade surface water quality and sensitive ecosystems that support threatened or endangered species (Tzilkowski et al., 2010; NYSDEC and PFBC, 2010), such as the federally endangered Dwarf Wedge Mussel (*Alasmidonta hereroden*). Of the few remaining populations of this species, one is found within the Neversink River, one in the mainstem of the upper Delaware River, and another within a small coldwater tributary of the middle river (Playfoot and Snyder, 2010). Dwarf wedge mussels are protected under the Endangered Species Act. It is critically important that pristine water quality conditions be maintained to protect this species.

49) There are real environmental, water quality, air quality, explosive, health, and endangered species concerns regarding gas exploitation below carbonate beds, inclusive of in caves. Carbonate formations in portions of the Delaware River Basin are recognized among karst

hydrologists as being karstic or cave/conduit bearing in nature. Contaminants that may enter karstic solution conduits, from below or above, would quickly degrade groundwater and surface water quality.

50) Carbonates of the Onondaga Formation and Helderberg group outcrop in portions of the Delaware River Basin (Figure 10; Veni, 2002). These carbonate formations, while stratigraphically lower than the Marcellus shale, overlie other shale beds that are gas rich (e.g., the Utica shale of the Trenton Group). These carbonate formations are recognized among karst hydrologists as being karstic or cave/conduit bearing in nature. An important aspect of karst is its effect on water supply and contaminant transport. Water in solution conduits can travel up to several kilometers per day, and contaminants can move at the same rate. This poses serious problems when monitoring for water quality. Contaminants enter the ground easily through sinkholes and sinking streams, and filtering is virtually non-existent. Even small solution conduits can transmit groundwater and contaminants hundreds of times faster than the typical unenlarged fracture network. Methane or drilling-related contaminants that may enter karstic solution conduits, from below or above, would quickly degrade groundwater and surface water quality. Because karst aquifers are extremely vulnerable, it would be prudent to characterize the environmental risks to them prior to conducting drilling activities.

51) Gas drilling activities may pose a health risk to cave-dwelling species and cavers, including the federally endangered Indiana bat (*Myotis sodalis*). The build up of methane and other toxic chemicals in caves and mines may pose both an explosive and health risk to cavers, cave scientists, and cave-dwelling fauna. People and bats in caves may potentially be overwhelmed by the build up of methane and other toxic chemicals. This could lead to their deaths via inhalation or via explosions similar to those that have occurred at wellheads above gas plays. If methane or LNAPLs were to seep or flow into caves (from below or from leaking surface holding pits) situated above gas-rich shales, caves might in effect become "confined spaces" - toxic to breathe in with great and, possibly, rapid exposure risk. Importantly, cave dwelling animals, such as bats (Figures 8 and 9), might have their already stressed populations (i.e., via White-Nose Syndrome; USGS, 2010) further decimated by gas field related contaminant excursions.

52) The endangered Indiana bat has one or more hibernacula in the Delaware River Basin stratigraphically above the Utica Shale. To protect these bats, the NYS Department of Environmental Conservation (i.e., State of New York) purchased Surprise Cave, located near Mamakating, NY (Sullivan County) some years ago. There may be other bat hibernacula within the Delaware River Basin. Contaminants that may migrate into areas inhabited by the Indiana Bat would constitute unauthorized taking of the bats under the Endangered Species Act.



## **Conclusions**

53) Significant natural seismic activity is well documented in and adjacent to the Delaware River Basin over an extended period of time. Ground motions from even one significant earthquake, among many that occur over time, may catastrophically shear numerous gas exploration and well casings or, at the very least, may result in fracturing and loss of integrity of well casing cement designed to isolate freshwater aquifers from deep saline waters. As such, earthquakes may instantly destroy the integrity of hundreds of gas wells, thereby forever and irreparably compromising the hydrologic integrity of geologic formations that formerly protected freshwater aquifers. Restoration of contaminated freshwater aquifers is probably not possible, thus well failures from any single or combination of mechanisms is likely an irrevocable commitment of natural resources.

54) The installation of exploratory wells that open borehole or nearby joint pathways between formerly separated geologic horizons pose an environmental risk, particularly because the area is seismically active. Ground motion associated with seismic activity has the real potential of instantly shearing multiple well casings throughout gas fields, degrading cement grout designed to isolate geologic horizons (i.e., freshwater aquifers), and thereby opening vertical joint and borehole vectors between formerly separated geologic horizons. Numerous earthquakes have occurred in Pennsylvania, New York, and adjacent states, pointing out that the region of the exploratory wells is seismically active.

55) Vertical exploration wells and related surface activities have the potential to permanently and irreparably harm ground and surface water resources in the Delaware River Basin. Extensive existing fracture and fault networks throughout the Appalachian Basin may provide upward pathways for contaminant and gas migration through geologic zones believed to be physically isolated, based on incomplete data. Although gas producers have asserted publicly that these zones are physically isolated, to date there are no publicly available studies to prove this claim. On the contrary, multiple studies indicate the presence of pervasive natural fracturing that will allow for migration to freshwater aquifers of methane, other hydrocarbons and their constituents, drilling fluids and materials, and naturally occurring hazardous materials including deep saline waters and NORMs. As a result, there are significant health and environmental risks associated with advancing exploratory gas wells in the Delaware River Basin and elsewhere in the Appalachian Basin.

56) The characterization of vertical fractures, faults, seismic hazards, casing and grout failures, contaminant hazards, and methane soil gas in the Delaware River Basin and elsewhere in the Appalachian Basin is not adequate to address potential adverse environmental impacts. Existing information does not sufficiently address pre-existing contaminant (i.e., gas and fluid) pathways that extend from the Marcellus shale to aquifers, surface water bodies, and the ground surface. Vertical exploratory wells, as well as future hydro-fracturing and enhancement of gas-bearing fractures may significantly increase gas excursions to formerly isolated geologic formations. Review of reports and news articles indicate that significant environmental contamination has occurred in geologically similar settings, including explosive hazards and groundwater and surface water contamination. This puts the Delaware River, its tributaries, and watershed at substantial risk of pollution and degradation.

57) Documentation by Jacobi of Fracture Intensification Domains based on methane soil gas anomalies over open fractures reveals evidence that naturally occurring fractures and faults provide upward gaseous migration pathways, even in the absence of deep hydro-fracturing in the Marcellus shale. If fracture and fault networks are intersected by vertical exploratory well completions and/or integrated and enlarged via hydro-fracturing processes, it is likely that methane, LNAPL, and radioactive gas excursions will increase.

58) The reality is that methane gas extraction from tight shale formations, including the Marcellus and similar formations throughout the country, have contaminated ground and surface waters. Reasons for this include poor containment of fracturing fluids, spills of flow-back water, intentional illegal disposal, mixing of different formation waters (e.g., brine and fresh water), inadequately grouted casing, failed grout, spills, and various forms of operator error. Gas production in the Delaware River Basin and elsewhere in the Appalachian Basin would almost certainly result in contaminant excursions, even under the best planned conditions. The presence of confirmed fractures and faults that extend from gas-rich geologic beds to the ground surface, some of which extend laterally for miles and are closely linked with others formed under similar structural conditions, pose potential contaminant pathways to surface waterways, reservoirs, and freshwater aquifers.

59) Because the density, location, aperture width, and length of all fractures (often present and not visible beneath a soil mantle) are not known, it would not be prudent to risk placement of numerous gas wells within sub-basins that contain lakes and reservoirs used for public water supplies. From a water quality standpoint four facts stand out: 1) there is a point at which the actual total number of toxic contaminants introduced into a groundwater flow system no longer matters because the water is unlikely to ever be potable again no matter how much money is spent attempting to remediate it, 2) new groundwater circulation pathways are likely to develop in response to repeated hydro-fracturing and newly available freshwater hydraulic/pressure heads, resulting in commingling of freshwater and contaminant-laden waters, 3) eventually, even deep groundwater flow systems discharge to surface water, albeit it may take many years to occur (i.e., analogous to a slowly ticking time bomb), and 4) it makes little sense to jeopardize the quality of surface and groundwater by intentionally introducing vast quantities of toxic contaminants into the environment, especially where gas-conducting fractures and faults are known to extend from gas-bearing formations to the ground surface.

60) It is important to recognize that once our natural resources have been compromised as a result of an operator error, grout and/or casing failure, a major contaminant excursion, seismic activity, or an unforeseen breaching of geologic beds, that it may be impossible to remediate and restore them to their pre-existing conditions. Failed confining beds and contaminated natural resources often represent an irrevocable commitment of our lands. Our decision to risk natural resources in the Delaware River Basin must weigh all the health and environmental risks against exploitation of relatively short-lived gas reserves and financial gain.

The opinions expressed herein are stated to a reasonable degree of scientific and professional certainty.

*Paul A. Rubin*

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### Figure Listing

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## Addenda Listing

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Addendum 1: Paul Rubin Resume

Addendum 2: Pennsylvania Earthquake History

Addendum 3: New York Earthquake History