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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 J2 joints draining to J1 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 <u>conservative</u> 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^2). 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, Lustgerten (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 irremediable 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

Paul A. Rubin

References

Bame, D. and Fehler, M., 1986, Observations of long period earthquakes accompanying hydraulic fracturing. Geophysical Research Letters, v. 13, no. 1, p. 149-152.

Bradley, W.H. and Pepper, J.F., 1938, Structure and gas possibilities of the Oriskany Sandstone in Steuben, Yates, and parts of the adjacent counties, New York: U.S. Geological Survey Bulletin, v. 899-A, p. 68.

COP – Commonwealth of Pennsylvania Consent Order and Agreement with Cabot Oil and Gas Corporation, Nov. 4, 2009. Order addresses failure to properly cement casings and failure to prevent the unpermitted discharge of natural gas, a polluting substance, from entering groundwater.

DCNR (Department of Conservation and Natural Resources, 2006, Earthquake hazard in Pennsylvania, Educational Series 10. First edition, June 1989; second edition, May 2003; slightly revised June 2006. Author: Charles K. Scharnberger, PA Geological Survey.

Dusseault, M.B., Gray, M.N. and Nawrocki, P.A., 2000, Why oilwells leak: cement behavior and long-term consequences. Society of Petroleum Engineers Inc. (SPE 64733). Paper prepared for presentation at the SPE International Oil and Gas Conference and Exhibition in China held in Beijing, China 7-10 November 2000.

Engelder, T., Lash, G.G., and Uzcátegui, 2009, Joint sets that enhance production from Middle and Upper Devonian gas shales of the Appalachian Basin. AAPG Bulletin; July 2009: v. 93; no. 7; p. 857-889.

Evans, M.A., 1994, Joints and decollement zones in Middle Devonian shales; evidence for multiple deformation events in the central Appalachian Plateau: geological Society of America Bulletin, v. 106, p. 447-460.

Feng, Q. and Lees, J.M., 1998, Microseismicity, stress, and fracture in the Coso geothermal field, California. Tectonophysics, v. 289, issues 1-3, p. 221-238.

Hazen and Sawyer, 2009, Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed, Rapid Impact Assessment Report. Sept. 2009. Prepared for NYCDEP.

Horálek, J., Dorbath, L., Jechumtálováa, Z., and Šilený, J., 2009, Source mechanisms of micro-earthquakes induced in hydraulic fracturing experiment at the HDR site Soultz-sous-Forêts (Alsace) in 2003 and their temporal and spatial variations. Geophysical Research Abstracts, v. 11, EGU2009-14008.

Jacobi, R.D., 2002, Basement faults and seismicity in the Appalachian Basin of New York State. Tectonophysics, v. 353, Issues 1-4, 23 August 2002, p. 75-113.

Jacobi, R.D. and Smith, G.J., 2000, Part I. Core and cutting analyses, surface structure, faults and lineaments, and stratigraphic cross-sections based on previous investigations. In: Jacobi, R.D., Cruz, K., Billman, D. (Eds.), Geologic Investigation of the Gas Potential in the Otsego County Region, Eastern New York State: Final Phase One Report to Millennium Natural Resources Development, L.L.C. NYSERDA, Albany, NY, 45 pp.

Kargbo, D.M., Wilhelm, R.G. and Campbell, D.J., 2010, Natural Gas Plays in the Marcellus Shale: Challenges and Potential Contaminants. Environmental Science and Technology, v. 44, pp. 5679 – 5684, June 2, 2010.

Lash, G.G. and Engelder, T., 2009, Tracking the burial and tectonic history of Devonian shale of the Appalachian Basin by analysis of joint intersection style. GSA Bulletin; Jan/Feb 2009; v. 121; no. ½; p. 265-277.

LI, Y-P, 1996, Microearthquake analysis for hydraulic fracturing process. Acta Seismologic Sinica, v. 9, no. 3, p. 377-387.

Lustgarten, A., 4-22-09, Digging at mystery of methane in wells - The Denver Post http://www.denverpost.com/news/ci_12195167#ixzz0ywZqfVcB; Article references work conducted by S.S. Papadopulos and Associates.

NYSDEC and PFBC, 2010, Recommended improvements to the flexible flow management program for Coldwater Ecosystem protection in the Delaware River Tailwaters. Authored by NYS Department of Environmental Conservation and Pennsylvania Fish and Boat Commission, 9 p.

Northrup, J.L., 2010, The Unique Environmental Impacts of Horizontally Hydrofracking Shale. Report of Otsego 2000 prepared for September 2010 public hearing.

Playfoot, K.M. and Snyder, E.M., 2010, Genetic relationships among Federally-endangered Alasmidonta heterodon within the Delaware River Basin. Penn State School of Forest Resources.

Rubin, P.A., Ayers, J.C., and Grady, K.A., 1992, Solution mining and resultant evaporite karst development in Tully Valley, New York. Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes Conference (3rd, Nashville, Tenn., Dec. 1991), Proceedings. National Ground Water Association, Dublin, Ohio, p. 313-328.

Shapiro, S.A. and Dinske, C., 2009, Fluid-induced seismicity: Pressure diffusion and hydraulic fracturing. Geophysical Prospecting, v. 57, p. 301-310.

Stiles, K., 2010, DRBC data request. E-mail dated 1-25-10 to David Kovach detailing drilling summary of Matoushek #1 well.

Taylor, R.G., 2009, Oil, oil and more oil: http://www.usgennet.org/usa/ny/county/allegany/OIL-COUNTY/OIL-OIL-MORE%20OIL.HTM (accessed by Engelder et al. - January 31, 2009)

Tzilkowski, C.J., Callahan, K.K., Marshall, M.R. and Weber, A.S., 2010, Integrity of benthic macroinvertebrate communities in the upper Delaware scenic and recreational river; Eastern rivers and mountains network 2008 summary report. Natural Resource Data Series NPS/ERMN/NRDS – 2010/029.

USGS, 2010, White-Nose Syndrome Threatens the Survival of Hibernating Bats in North America. Web page information from Fort Collins Science Center: http://www.fort.usgs.gov/wns/

Veni, G., 2002, Revising the karst map of the United States. Journal of Cave and Karst Studies, v. 64, no. 1, p. 45-50.

Zhou, Z., He, J., Huang, M., He, J., and Chen, G., 2010, Casing Pipe Damage Detection with Optical Fiber Sensors: A Case Study in Oil Well Constructions; In Advances in Civil Engineering, v. 2010, Article ID 638967, 9 pages.

Figure Listing

Available at http://hydroquest.com/Riverkeeper/

Addenda Listing

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Addendum 1: Paul Rubin Resume
Addendum 2: Pennsylvania Earthquake History
Addendum 3: New York Earthquake History

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EDUCATION:

M.A. - Geology, May 1983, State University of New York at New Paltz. Major fields of study: Hydrogeology, Water Quality and Pollution, Structural Geology, Photogeologic Interpretation. Thesis topic: *Hydrogeology and Structure of the Shawangunk Mountains, Ulster County, New York.*
B.A. - Anthropology, minor Geology, May 1977. State University of New York at Albany.

SPECIAL SKILLS:

Environmental Impact Statement (EIS) Analyses; Determination & Findings of Significant Impacts or Lack Thereof (e.g., FONSI & Negative Declarations); Environmental Protection; Hydrologic and Geologic Characterizations; Land Use Planning & Characterizations; State Environmental Quality Review Act (SEQRA) reviews; Evaluation of Physical & Human Environments via Remote Sensing, Photogrammetric Analysis & Field Reconnaissance; Habitat and Water Quality Based Analyses specific to Threatened, Endangered & Other Species; Expert Testimony and Litigation Background; Surface Water and Groundwater Quality Evaluations; Sediment Transport; Evaluation of Remedial Technologies; Geotechnical Assessments; Hydrologic Investigations; Aquifer Testing and Analysis; Karst Hydrology; Rosgen Stream Analyses; Flood Return Analyses; GIS Map Making and Analyses; Photogrammetric Analyses; Affidavit and Report Preparation; Educator; Public Speaking; Public Relations; Research Skills; Strategy Development; Leadership.

EXPERIENCE:

HYDROLOGIST/HYDROGEOLOGIST:

1993 - Present

Independent Consultant. Stone Ridge, New York. Consulting firm: *HydroQuest*. Provide hydrologic, geologic and land use technical consulting services to environmental groups, Towns, business associations, law firms, and individuals. Assist groups in identifying issues and developing strategies designed to protect groundwater and surface water resources, community character, and wildlife habitat.

***HydroQuest* work includes SEQRA reviews, review and fatal flaw analyses of consultant reports and environmental impact statements (EISs); environmental scoping report preparation; direction and oversight of heavy equipment operators for field excavation work for well placements, contaminant characterization, and geologic investigations; technical coordination of scientific case development for environmental groups and attorneys; field characterizations; stream and wetland evaluations; geotechnical analyses; hydrologic and geologic mapping; water quality assessments; watershed delineations; viewshed analyses; slope analyses; aquifer analyses; hydrogeologic analyses; regulatory assessments; GIS map preparation; public presentations; technical presentations to judges; coordination work with attorneys and Technical Committees; direction and coordination of sub-contract work as needed; strategy development; panel member at Town meetings with legislators; press interactions; report and affidavit preparation. Recently provided major report input on gas drilling & hydrofracturing.**

Recent project work examples include oversight and analysis of well field pumping tests (for multiple groups including NRDC, NYPIRG, Riverkeeper, and Trout Unlimited) designed to assess impacts on groundwater and surface water stemming from a planned large-scale Catskill Mountain resort; assessment of a town's water quality problem with corrective recommendations; initial hydrogeologic assessment of a spring water source being considered for bottled water use; hydrogeologic-aquifer analysis of a groundwater supply proposed for a Shawangunk Ridge retreat center; SEQRA assessments; and technical presentations and testimony before administrative law judges.

KARST HYDROLOGIST

Howe Caverns, Inc. Cobleskill, New York. 2nd largest natural tourist attraction in NYS

2004 - April 2007 **Conducted hydrologic and geologic research, produced professional GIS maps and figures, developed educational programs and materials, developed new tourist route, trained guides, provided land use assessments and recommendations, advised the Board of Directors on land use concerns including potential water quality degradation and potential blast-related impacts to cave. Developed and proposed revenue generating strategies. Coordinated with outside educational institutions, professional geologists, learning institutions, and scout groups. Formerly worked in this position half-time prior to change in ownership.**

INSTRUCTOR:

Jan. 2001- Dec. 2004 **SUNY Ulster, Stone Ridge, New York.**
Taught ArcGIS, Environmental Geology, Geology, Hydrology, Geography, and Crime Analysis. Coordinator of a Geographic Information Systems certificate program. Developed, obtained, and completed a NYSDEC grant to assess assorted hydrologic and environmental aspects of the Black Creek watershed in Ulster County. Supervision and oversight of numerous professional adult "students", directed GIS-based technical presentations, and coordinated and produced grant products.

College of the Atlantic, Bar Harbor, Maine.
Taught a two week graduate level summer field hydrology and environmental science course for several years, including Rosgen stream assessment.

HYDROLOGIST:

New York City Department of Environmental Protection (NYC DEP), Division of Drinking Water Quality Control, Shokan, New York.

April 1993- Jan. 2001 **Conducted research and field studies designed to assess the water quality of watersheds. Responsible for directing geologic research designed to assess the sources, geomorphic context and best management practices (BMPs) related to sediments causing turbidity water pollution problems. Hydrologic and geologic work included geologic mapping of glacial sediments, field evaluation of stream channel armoring, morphologic characterization of stream channels (including Rosgen analyses), bedload transport studies, assessment of critical shear stresses, particle size analysis, stream gauging, water quality sampling and trend analysis, chemical and sediment loading calculations, graphic production, report preparation and technical presentations. Assisted other governmental divisions in evaluating lands for possible purchase, conducted geotechnical assessments of structurally unstable stream reaches, evaluated BMP designs. Supervised several Research Assistants.**

RESEARCH SCIENTIST:

Martin Marietta Energy Systems, Inc. April 1993 under contract with the U.S. Dept. of Energy; Oak Ridge National Lab; Environmental Sciences Division, Oak Ridge, TN.

Aug. 1991- April 1993 **Responsible for hydrogeologic evaluation of groundwater issues (e.g., characterization, monitoring network setup, data analysis, remedial design evaluation) at multiple Oak Ridge Reservation hazardous waste sites. Developed and documented conceptual model of carbonate and shallow storm flow systems comprising pathways of rapid contaminant transport. Work also involved characterization of hydrologic and geochemical trends**

RESEARCH SCIENTIST continued:

and thermal infrared photo analysis. Presented results of research at conferences, as well as to DOE management and State and Federal officials. *Served in a Resource Management Organization as the hydrologic lead for the Environmental Sciences Division.*

HYDROGEOLOGIST:

New York State Attorney General's Office; Environmental Protection Bureau, Albany, New York.

Feb. 1983-
Aug. 1991

Responsible for the design, protocols, coordination, implementation, evaluation, characterization and remediation of many major water and soil contamination sites throughout New York State (e.g., Love Canal, Superfund sites). Designed, performed and supervised chemical field sampling at hazardous waste sites. Evaluated geotechnical and chemical data sets.

Primary responsibilities included coordination of multiple companies along with their respective legal and scientific consultants. Worked with all parties involved to produce test plans and consent decrees to facilitate site remediation. Responsible for the management of the testing, site characterization and technical assessment. Worked with attorneys on summary judgment motions, complaints, trial preparation and depositions. Attorney General's spokesperson at public meetings. Expert witness at SEQRA hearings. Testimony given before the Assembly Standing Committee on Environmental Conservation and Grand Jury. Worked with DOL staff and attorneys to develop office initiatives (e.g., Racketeering; bottled water contaminants). Initiation, development and drafting of legislation.

Supervision of personnel: expert witnesses, consultants, research assistants, interns. Responsible for selection, job descriptions, work schedules, and products.

HYDROGEOLOGIST:

Stone & Webster Engineering Corp., Geotechnical Division, Boston, Massachusetts.

Oct. 1981-
Feb. 1983

Directly responsible for the planning, preparation, execution, and analysis of pumping tests and a fluid sampling program designed to investigate deep basin groundwater characteristics for the siting of a nuclear waste repository within the Permian Basin of the Texas panhandle. Planned, managed, coordinated, directed, and provided oversight of field operations of a multi-million dollar project. Sub-contractors included Halliburton, Schlumberger, and others.

ACTIVITIES:

Hiking, cave research, and exploration. Former Captain: Albany-Schoharie County Cave Rescue Team. Made a Fellow of the National Speleological Society in recognition of karst research and water resource protection.

PUBLICATIONS & REPORTS

Over 50 technical publications and over 100 reports and affidavits, many for private clients, environmental groups, towns, and law firms. Projects include land, wetland, water quality, and species protection; aquifer and watershed characterization; mine proposals; development proposals; contaminant assessments; stream hydrology grant work; and flood risk. Some reports are confidential. Leader of geology conference field trips for groups including the New York State Geological Association, the American Institute of Professional Geologists, the Hudson-Mohawk Professional Geologists' Association, the National Ground Water Association, the National Speleological Society, and the International Association of Geochemists and Cosmochemists.

ADDENDUM - SELECTED PUBLICATIONS

SELECTED PUBLICATIONS FROM PROFESSIONAL AND PERSONAL RESEARCH

Rubin, P.A., 2009, ***Geological Evolution of the Cobleskill Plateau; New York State, USA,*** in Veni et al. (eds), Proceedings of the Speleogenesis Symposium of the 15th International Congress of Speleology (joint National Speleological Society & Union Internationale de Speleologie); Symposium: Speleogenesis in Regional Geological Evolution and its Role in Karst Hydrogeology and Geomorphology, Kerrville, Texas. Proceedings, Volume 2, Symposia Part 2, pages 972-978 (published July 2009).

Palmer, A.N. and Rubin, P.A., 2007, ***Karst of the Silurian-Devonian Carbonates in Eastern New York State, with emphasis on the Cobleskill Plateau***. Guidebook for the Hudson-Mohawk Professional Geologists' Association Spring 2007 Field Trip, *"Carbonate Geology of the Howes Cave Area, Schoharie County, New York"*, p. 17-35, Trip coleader with Arthur Palmer (April 28, 2007).

Rubin, P.A., Burmeister, K.C. and Folsom, M., 2006, ***Karst Resource Management: groundwater protection and developmental considerations in the Kingston-Rosendale aquifer system***; Ulster County, N.Y., Poster Presentation at the 2005 National Cave and Karst Management Symposium. Report prepared for Scenic Hudson.

Stokowski, S., Rubin, P.A. and Guenther, B., 2006, ***History of resource management: conflict and resolution, Howes Cave, N.Y.***, in Rea, G.T., (ed), Proceedings of the 2005 National Cave and Karst Management Symposium.

Rubin, P.A and Stokowski, S., 2004, ***Karst, Caves, and Quarries***. Guidebook paper for ***the*** American Institute of Professional Geologists (AIPG), Annual Meeting. Field trip co-leader.

Rubin, P.A. and Washington, G., 2004, ***Water quantity and quality considerations specific to development on the flank of the Shawangunk Mountain Ridge, Southeastern NYS.*** Abstracts Northeast Natural History Conference VIII. N.Y. State Museum Circular 66: p. 53.

Rubin, P.A., Adickes, D.M., Cunningham, T., Davidson, D., Hurld, J. Kiyan, J.R., Preuss, P., Ramsay, W., Schultz, B. and Washington, George, 2004, ***Application of GIS technology to assess visual impacts of development: Shawangunk Ridge case study, southeastern NYS***. Abstracts Northeast Natural History Conference VIII. N.Y. State Museum Circular 66: p. 52-53.

Adickes, D.M., Preuss, P., Rubin, P.A., and Thompson, J., 2004, ***GIS assessment and study of rare and threatened avian species living in the Shawangunk Mountains in Southeastern NYS***. Abstracts Northeast Natural History Conference VIII. N.Y. State Museum Circular 66: p. 38.

Kiyan, J.R., Washington, G., and Rubin, P.A., 2004, ***GIS visual impact analysis of a proposed housing development below Minnewaska State Park Preserve in the Shawangunk Mountains of the Mid-Hudson Valley in New York State***. Abstracts Northeast Natural History Conference VIII. N.Y. State Museum Circular 66: p. 47.

Cunningham, T., Davidson, D., Hurld, Rubin, P.A., and Ehrensaft, P., 2004, ***Using GIS technology to project various land-use and economic scenarios for the northern Shawangunk Ridge area; Southeastern NYS***. Abstracts Northeast Natural History Conference VIII. N.Y. State Museum Circular 66: p. 41-42.

Palmer, A.N., Rubin, P.A., Palmer, M.V., Engel, T.D., and Morgan, B., 2003, ***Karst of the Schoharie Valley, New York.*** Guidebook for the New York State Geological Association Diamond Jubilee Field Conference (75th Annual Meeting), p. 141-176, Trip coleader.

Rubin, P.A., Morgan, B., and Palmer, A.N., 2003, ***Howe Caverns resource protection: hydrology and land-use analysis; Schoharie County***, New York State. Abs. Northeastern Science Foundation Silver Jubilee Anniversary Symposium, Proceedings volume, p. 25-26.

Rubin, P.A., Hubsch, R., Albrechtsen, C.A., Black, G., Folsom, M., Keller, J., Morgan, B., Ortega, A., Rodden, M., Schultz, B., Terzella, D., and Washington, G., 2003, ***Watershed management and protection planning based delineation of critical environmental areas via GIS analysis***. Abs. Northeastern Science Foundation Silver Jubilee Anniversary Symposium, Proceedings volume, p. 13.

Hubsch, R., Morgan, B., Black, G., Folsom, France, N., Keller, J., Ortega, A., Post, J., and Rubin, P.A., 2003, ***Development of a GIS-based land-use coverage: Black Creek and Swarte Kill watersheds, southeastern New York State***. Abs. Northeastern Science Foundation Silver Jubilee Anniversary Symposium, Proceedings volume, p. 9-10.

Rubin, P.A., Waines, R., Washington, G., Ortega, A., Albrechtsen, C.A., Hubsch, R., Folsom, M., Keller, J., Morgan, B., and Schultz, B., 2003, ***Hydrology and geology of the Swarte Kill and Black Creek basins, eastern New York State***. Abs. Northeastern Science Foundation Silver Jubilee Anniversary Symposium, Proceedings volume, p. 12.

Rubin, P.A., Engel, T., Nardacci, M. and Morgan, B.E., 2002, ***Geology and paleogeography of Mount Desert Island and surrounding area, Maine.*** Guidebook paper National Speleological Society annual meeting, Camden, Maine, p. 47-91, Trip leader.

Rubin, P.A., Schultz, B. and Haberland, P., 2002, ***Hydrologic, land use, and historic concerns relative to the Rosendale mining industry.*** Abs. National Speleological Society annual meeting, Camden, Maine, p. A-27.

Rubin, P.A. and Morgan, B., 2002, ***Relict sea caves record temporary coastal stillstands.*** Abs. National Speleological Society annual meeting, Camden, Maine, p. A-26-A-27.

Morgan, B., Albrechtsen, C., Dido, R., Hubsch, R., Rubin, P.A., Sheeley, D., Skerritt, F. and Vaeth, L., 2002, ***Development of a GIS-based land-use coverage: Black Creek Watershed, Southeastern NYS.*** Abs. Northeast Natural History Conference VII. N.Y. State Museum Circular 64: p. 50-51.

Hubsch, R., Albrechtsen, C., Dido, R., Morgan, B., Rubin, P.A., Sheeley, D., Skerritt, F., Terzella, D. and Vaeth, L., 2002, ***Critical environmental area delineation in the Black Creek Watershed, NYS via GIS analysis.*** Abs. Northeast Natural History Conference VII. N.Y. State Museum Circular 64: p. 51.

Sheeley, D.A. and Rubin, P.A., 2002, ***Land-use preservation scenarios in the Black Creek Watershed using GIS; NYS.*** Abs. Northeast Natural History Conference VII. N.Y. State Museum Circular 64: p. 51.

Schultz, B., Rubin, P.A. and Haberland, P., 2002, ***GIS-based historic inventory of early cement district industrial artifacts: Southeastern NYS***. Abs. Northeast Natural History Conference VII. N.Y. State Museum Circular 64: p. 40.

Rubin, P.A. and Morgan, B., 2002, ***Geomorphic reconstruction of emerged and submerged coastlines using GIS technology, Mount Desert Island, ME.*** Abs. Northeast Natural History Conference VII. N.Y. State Museum Circular 64: p. 39.

Rubin, P.A. and Privitera, J.J., 1997, ***Engineered and*** **unregulated degradation** ***of karst aquifers: Two case studies in New York State, USA.*** *In* The Engineering Geology and Hydrogeology of Karst Terranes, Beck & Stephenson (eds), Proceedings of The Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst; Balkema, Rotterdam; p. 467-476.

Rubin, P.A., Engel, T., and Nardacci, M., 1995, ***Geomorphology, paleoclimatology and land use considerations of a glaciated karst terrain, Albany County, New York.*** Guidebook for joint meeting of the New York State Geological Association (67th Annual) and the American Association of Petroleum Geologists. Trip leader, p. 81-107.

Rubin, P.A., 1995, ***The geology of Clarksville Cave, Albany County, New York.*** Guidebook for joint meeting of the New York State Geological Association (67th Annual) and the American Association of Petroleum Geologists. Trip leader, p. 251-273.

Rubin, P.A., 1995, ***The geology of Cherokee Caverns; Tennessee***. *In* Karst Geohazards (ed. by B. Beck), Proceedings of: The Fifth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst; Sponsors include the National Ground Water Association and the American Society of Civil Engineers, Gatlinburg, TN, p. 541-547.

Rubin, P.A., 1994, ***Paleohydrology of the Kämper Avenue area; Mammoth Cave National Park, Kentucky.*** Mammoth Cave National Park's Third Science Conference; Sponsored by Mammoth Cave National Park and The Cave Research Foundation, Mammoth Cave National Park, Kentucky, p. 265-279.

Rubin, P.A., Zerr, B., Davies, G.J., Lemiszki, P.J., Neuhoff, P.S., and Aiken, J., 1993, ***Preliminary hydrogeologic studies in carbonate aquifers of the Oak Ridge Reservation, Tennessee.*** Abs. Fourth Annual Walker Branch Watershed Research Symposium, Oak Ridge, TN, p. 15-16.

Davies, G.J., Rubin, P.A., and Quinlan, J.F., 1993, ***Indirect observation of the rapid-flow and slow-flow components of recharge to the Knox aquifer, Oak Ridge, Tennessee.*** Abs. Fourth Annual Walker Branch Watershed Research Symposium, Oak Ridge, TN, p. 17.

Rubin, P.A., Lemiszki, P.J., and Poling, R.S., 1992, ***Strategy for definition and protection of East Tennessee karst groundwater basins.*** Tennessee Water Resources Symposium (5th, Nashville, TN., Oct. 1992), Proceedings. American Water Resources Association, Nashville, TN, p.7-10.

Rubin, P.A. and Lemiszki, P.J., 1992, ***Structural and stratigraphic controls on cave development in the Oak Ridge area, Tennessee.*** Tennessee Water Resources Symposium (5th, Nashville, TN., Oct. 1992), Proceedings. American Water Resources Association, Nashville, TN, p. 111-117.

Rubin, P.A., Lietzke, D.A., and Schmidt, V.A., 1992), ***Aspects of the geomorphology of Oak Ridge, Tennessee.*** Abs. National Speleological Society Convention, Salem, IN.

Rubin, P.A., 1992, ***Strategy for aquifer and stream protection in karst terranes.*** Abs. The New York Natural History Conference II, New York State Museum Circular 54, p. 61, Albany, New York.

Rubin, P.A., 1992, ***Karst hydrology of Oak Ridge, Tennessee.*** Abs. Third Annual Walker Branch Watershed Research Symposium, Oak Ridge, TN, p. 34.

Rubin, P.A., 1992, ***Land-use planning and watershed protection in karst terranes.*** Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes Conference (3rd, Nashville, Tenn., Dec. 1991), Proceedings. National Ground Water Association, Dublin, Ohio, p. 769-793.

Rubin, P.A., Ayers, J.C., and Grady, K.A., 1992, ***Solution mining and resultant evaporite karst development in Tully Valley, New York.*** Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes Conference (3rd, Nashville, Tenn., Dec. 1991), Proceedings. National Ground Water Association, Dublin, Ohio, p. 313-328.

Palmer, A.N., Rubin, P.A., and Palmer, M.V., 1991, ***Interaction between karst and glaciation in the Helderberg Plateau, Schoharie and Albany Counties, New York.*** Guidebook for New York State Geological Association Annual Meeting, Oneonta, New York, p. 161-190.

Palmer, A.N., Palmer, M.V., Porter, C.O., Rubin, P.A., and Mylroie, J.E., 1991, ***A geological guide to the karst and caves of the Helderberg Mountains, Schoharie and Albany counties, New York.*** Guidebook paper for National Speleological Society annual meeting, Cobleskill, New York, p. 105-167.

Rubin, P.A., 1991, ***Modification of preglacial caves by glacial meltwater invasion in East-Central New York.*** Appalachian Karst Symposium, Proceedings. National Speleological Society, Radford, Virginia, p. 91-100.

Rubin, P.A., 1991, ***Flow characteristics and scallop forming hydraulics within the Mill Pond Karst Basin, East-Central New York.*** Appalachian Karst Symposium, Proceedings. National Speleological Society, Radford, VA., p. 101-108.

Rubin, P.A., 1991, ***Emerged sea caves and coastal features as evidence of glacio-isostatic rebound, Mount Desert Island, Maine.*** Appalachian Karst Symposium, Proceedings. National Speleological Society, Radford, Virginia, p. 75-83.

Rubin, P.A., 1983, ***Structural geology and geomorphology of the Shawangunk Mountain caprock, Southeastern New York.*** Abs. Geol. Soc. Amer. N.E. Ann. Mtg., Kiamesha Lake, New York; and Abs. Mohonk Research Associates Conference, Mohonk Lake, New York.

Rubin, P.A. and Briedis, J., 1982, ***Acid precipitation and volcanism linked to Mesozoic dinosaur extinction.*** Abs. Geol. Soc. Amer. Ann. Mtg., New Orleans, Louisiana.

Rubin, P.A., Smiley, D., and Egemeier, S.J., 1981, ***Acid precipitation in the Shawangunk Mountains, Southeastern New York.*** Abs. AMS/CMOS International Conference on Long-Range Transport of Airborne Pollutants, Albany, New York; and Abs. Geol. Soc. Amer. N.E. Ann. Mtg., Bangor, Maine.

Rubin, P.A., 1981, ***New Aspects of the stratigraphy and structure of the Shawangunk Mountains, Southeastern New York.*** Abs. Geo. Soc. Amer. N.E. Ann. Mtg., Bangor, Maine.

Egemeier, S.J., Liff, C.I., Smiley, D., and Rubin, P.A., 1981, ***The safe yield of the "sky" lakes of the Shawangunk Mountains of Southeastern New York***. Abs. Geol. Soc. Amer. N.E. Ann. Mtg., Bangor, Maine.

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Earthquake Hazards Program

Pennsylvania

Earthquake History

Record of early earthquakes in the Northeastern United States provide limited information on effects in Pennsylvania until 1737, 55 years after the first permanent settlement was established. A very severe earthquake that centered in the St. Lawrence River region in 1663 may have been felt in Pennsylvania, but historical accounts are not definite. Likewise, a damaging shock at Newbury, Massachusetts, in 1727 probably affected towns in Pennsylvania. A strong earthquake on December 18, 1737, toppled chimneys at New York City and was reported felt at Boston, Massachusetts, Philadelphia, Pennsylvania, and New Castle, Delaware. Other shocks with origins outside the State were felt in 1758, 1783, and 1791. In 1800, two earthquakes (March 17 and November 29) were reported as "severe" at Philadelphia. On November 11 and 14, 1840, earthquakes at Philadelphia were accompanied by a great and unusual swell on the Delaware River.

Dishes were thrown from tables (intensity V) at Allentown by a strong shock on May 31, 1884. Thirty towns from Hartford, Connecticut, to West Chester, Pennsylvania, reported fallen bricks and cracked plaster from an earthquake apparently centered near New York City on August 10, 1884. A tremor, described as lasting 10 seconds, was felt on March 8, 1889, at Harrisburg, Philadelphia, Reading, York, and other towns in that area. The intensity was estimated at V. An extremely local earthquake on May 31, 1908, at Allentown shook down a few chimneys (VI). The disturbance was not felt over more than 150 square kilometers.

On October 29, 1934, a shock of intensity V was felt at Erie. Buildings swayed, people left theaters, and dishes were thrown from cupboards. The earthquake was felt with lesser intensity at Edinboro, Girard, Mill Village, North East, and Waterford. Another shock with very localized effects occurred in southern Blair County on July 15, 1938. Broken dishes and fallen plaster (VI) were reported at Clover Creek and Henrietta. Wells were affected in Clover Creek Valley.

The area around Sinking Spring, west of Reading, experienced minor damage from an earthquake on January 7, 1954. Plaster fell from walls (VI), dishes and bottles tumbled from shelves, and furniture was upset. Other slight damage to several brick and frame buildings was reported. The tremor was felt in western Berks County and eastern Lancaster County. During the rest of the month, many smaller shocks were felt in the vicinity of Sinking Spring.

A local disturbance probably caused by subsidence of an underground coal mine caused damage estimated at $1 million in a five-block residential area of Wilkes-Barre on February 21, 1954. Occupants fled into the street. Hundreds of homes were damaged, ceilings and cellar walls split and backyard fences fell over. Sidewalks were pushed sharply upward by a heaving motion and then collapsed. Gas and water mains snapped; methane gas rising from cracks in the earth presented a temporary emergency. Two days later (February 23), a second disturbance was reported from the same section of Wilkes-Barre. More cracks appeared in ceilings and walls of apartment buildings. Curbs pulled away from sidewalks, and street pavements buckled. Additional water and gas mains were broken.

On September 14, 1961, a moderate earthquake that was centered in the Lehigh Valley shook buildings over a broad area and alarmed many residents. There was only one report of damage - loose bricks fell from a chimney at Allentown (V). However, police and newspaper switchboards throughout the area were swamped with calls from citizens. Other places with intensity V effects included Bethlehem, Catasauqua, Coplay, Egypt, Fountain Hill, Freemansburg, Hellertown, and Weaverville.

A similar disturbance occurred on December 27, 1961, in the northeast portion and suburbs of Philadelphia. Buildings shook, dishes rattled, and other objects were disturbed. Police and newspaper offices received many calls from alarmed citizens inquiring about the loud rumbling sounds (V). Several New Jersey communities across the Delaware River experienced similar effects.

A strong local shock, measured at magnitude 4.5, cracked a wall and caused some plaster to fall (VI) at Cornwall on May 12, 1964. Slight landslides were reported in the area. In one building, a radio was knocked from a table and a wall mirror moved horizontally. Workers in an iron mine about 360 meters underground were alarmed by a "quite sever jarring motion."

A small earthquake whose epicenter was in New Jersey caused intensity V effects at Darby, and Philadelphia. The December 10, 1968, shock was measured at magnitude 2.5. Although relatively minor, it broke windows at a number of places in New Jersey. Toll booths on the Benjamin Franklin and Walt Whitman Bridges in Philadelphia trembled during the earthquake.

On December 7, 1972, slight damage (V) was reported at New Holland. In addition, Akron, Penryn, and Talmage experienced intensity V effects. The total area covered approximately 1,200 square kilometers of Berks and Lancaster Counties.

Abridged from Earthquake Information Bulletin, Volume 8, Number 4, May - June 1973, by Carl A. von Hake.

For a list of earthquakes that have occurred since this article was written, use the Earthquake Search.

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http://earthquake.usgs.gov/earthquakes/states/pennsylvania/history.php

Earthquake Hazards Program

New York

Earthquake History

Strong earthquakes in 1638, 1661, 1663, and 1732 in the St. Lawrence Valley and a shock near Newbury, Massachusetts, in 1727 were felt in New York before the first notable tremor centered within the State was recorded. On December 18, 1737, an earthquake near New York City threw down a number of chimneys (intensity VII). This shock was reported felt at Boston, Philadelphia, and at New Castle, Delaware.

Walls vibrated, bells rang, and objects fell from shelves (intensity VI) at Buffalo from a shock on October 23, 1857. Also, a man seated on a chair was reportedly thrown to the ground. At Lockport, rumbling noises were heard for a full minute. This shock was felt as far as Hamilton, Peterborough, and Port Hope, Ontario, Canada; Rochester, New York; and Erie and Warren, Pennsylvania. The total felt area covered approximately 46,000 square kilometers.

A rather severe earthquake centered in northeastern New York caused moderate damage along the St. Lawrence River and in the Lake Champlain area in 1877. Crockery was overturned, ceilings cracked, and chimneys were thrown down (intensity VII) from the November 4 tremor. At Saratoga Springs, buildings were shaken and a roaring sound was heard; at Auburn, windows were damaged. The earthquake was felt throughout a large part of New York and New England and eastern Canada, about 233,000 square kilometers.

On August 10, 1884, an earthquake caused large cracks in walls at Amityville and Jamaica (intensity VII). The shock was felt strongly at New York City. In addition, 30 towns from Hartford, Connecticut, to West Chester, Pennsylvania, reported fallen bricks and cracked plaster. The total felt area was estimated at 181,000 square kilometers.

A shock reported as severe, but with no damage noted (intensity VI), occurred in northeastern New York on May 27, 1897. It was felt over the greater portion of New York and parts of adjacent New England States and Quebec, Canada.

A very large area of the northeastern United States and eastern Canada, about 4,200,000 square kilometers, was shaken by a magnitude 7 earthquake on February 28, 1925 (March 1, universal time). A maximum intensity of VIII was reached in the epicentral region, near La Malbaie, Quebec, Canada. A large portion of New York State experienced intensity IV effects; lesser intensities were noted south of Albany.

Extensive damage occurred in the Attica area from a strong shock on August 12, 1929. Two hundred and fifty chimneys were thrown down, plaster was cracked or thrown down, and other building walls were noticeably damaged (intensity VIII). Many cemetery monuments fell or were twisted. Dishes fell from shelves, pictures and mirrors fell from walls, and clocks stopped. An increased flow at the Attica reservoir was noted for several days after the earthquake; a number of wells near the reservoir went dry. There was some damage at Batavia and other points at similar distances. A wall was cracked at Sayre, Pennsylvania. The earthquake was felt throughout most of New York and the New England states, northeastern Ohio, northern Pennsylvania, and southern Ontario, Canada; a total area of about 250,000 square kilometers. Strong aftershocks were felt at Attica on December 2 and 3; dishes fell from shelves and clocks stopped.

The opposite end of the State experienced similar damage from another shock less than 2 years later. On April 20, 1931, an earthquake centering near Lake George threw down about 20 chimneys at Warrensburg and twisted a church spire (intensity VII). A small landslide was reported on McCarthy Mountain. At Glen Falls, walls were cracked, dished broken, and clocks stopped. At Lake George, buildings swayed and store goods fell from shelves. At Luzerne, some Chimneys were damaged and windows broken. The shock was felt over 155,000 square kilometers, but with less intensity in the Catskills than at equal distances in other directions. This anomaly was also noted in the August 12, 1929, Attica earthquakes.

The magnitude 6 1/4 earthquake centered near Timiskaming, Quebec, Canada, on November 1, 1935, caused slight damaged at many points in New York. The damage was limited, in general, to plaster cracks, broken windows, and cracked chimneys. The shock was felt throughout New York, as far south as Washington, D.C., and as far west as Wisconsin. An earthquake centered near Lake Ossipee, New Hampshire on December 24, 1940, caused widespread, though slight, damage in the epicentral region, extending into Maine, Massachusetts, Rhode Island, and Vermont. Reports from Dannemora, New York, noted plaster and windows cracked and some dishes broken. The shock was felt over all of New York State.

On September 4, 1944, an earthquake centered about midway between Massena, New York, and Cornwall, Ontario, Canada, caused an estimated $2,000,000 damage in the two cities. The shock destroyed or damaged about 90 percent of the chimneys at Massena (intensity VIII), with similar effects at Cornwall. In addition, masonry, plumbing, and house foundations were damaged at Massena. Many structures were rendered unsage for occupancy until repaired. Press reports indicated a large number of wells in St. Lawrence County went dry, causing acute hardship. Brick masonry and concrete structures were damaged at Hogansburg; some ground cracking was also noted at nearby towns. This earthquake was felt over approximately 450,000 square kilometers in the United States, including all the New England States, Delaware, Maryland, New Jersey, Pennsylvania, and portions of Michigan and Ohio. A few points in Illinois, Indiana, Virginia, West Virginia, and Wisconsin also reported feeling the tremor.

A magnitude 4.7 disturbance on January 1, 1966, caused slight damage to chimneys and walls at Attica and Varysburg. Plaster fell at the Attica State Prison and the main smokestack was damaged (intensity VI). The total felt area was about 46,500 square kilometers.

Abridged from Earthquake Information Bulletin, Volume 7, Number 4, July - August 1975, by Carl A. von Hake.

http://earthquake.usgs.gov/earthquakes/states/new_york/history.php

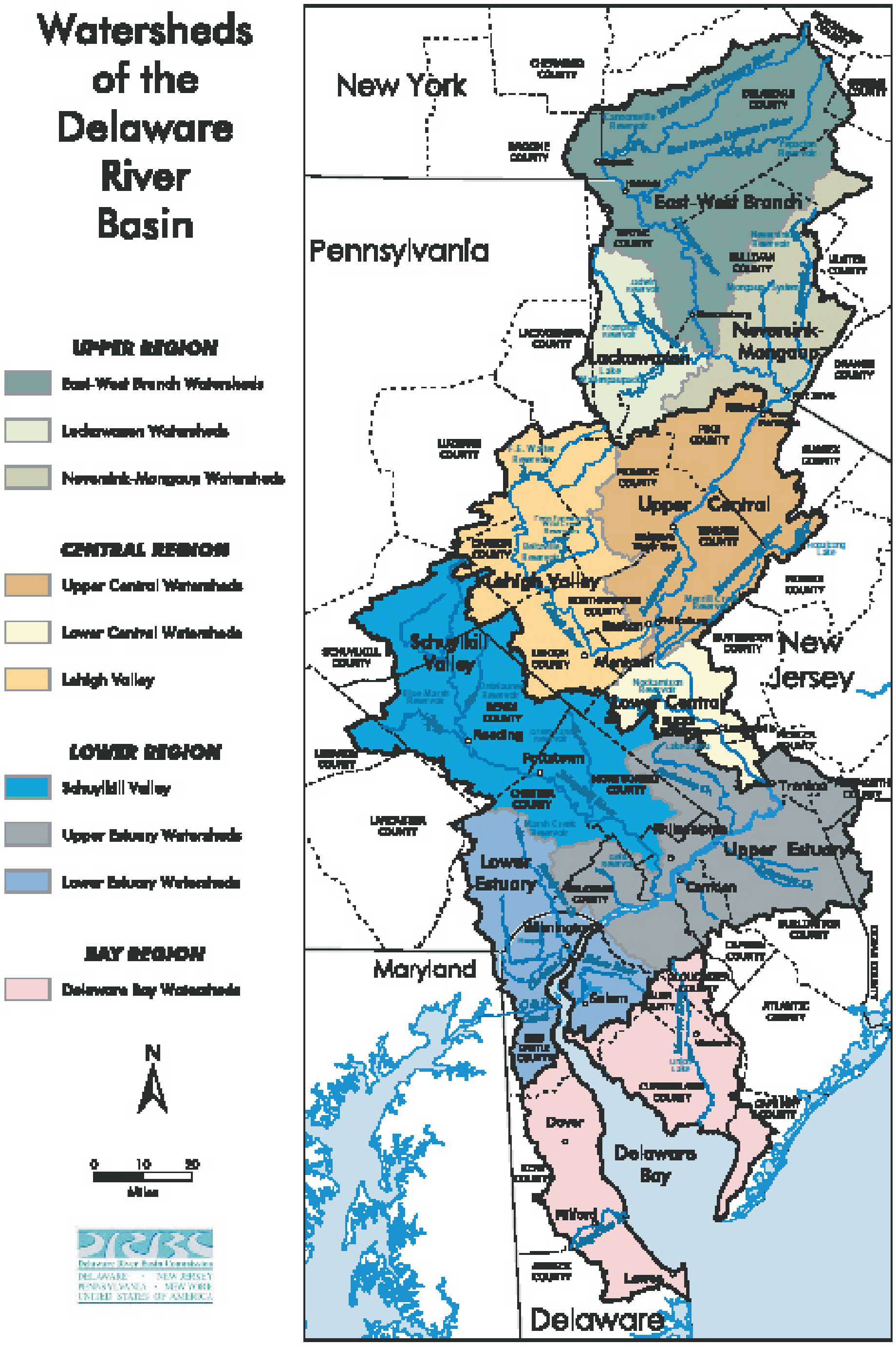
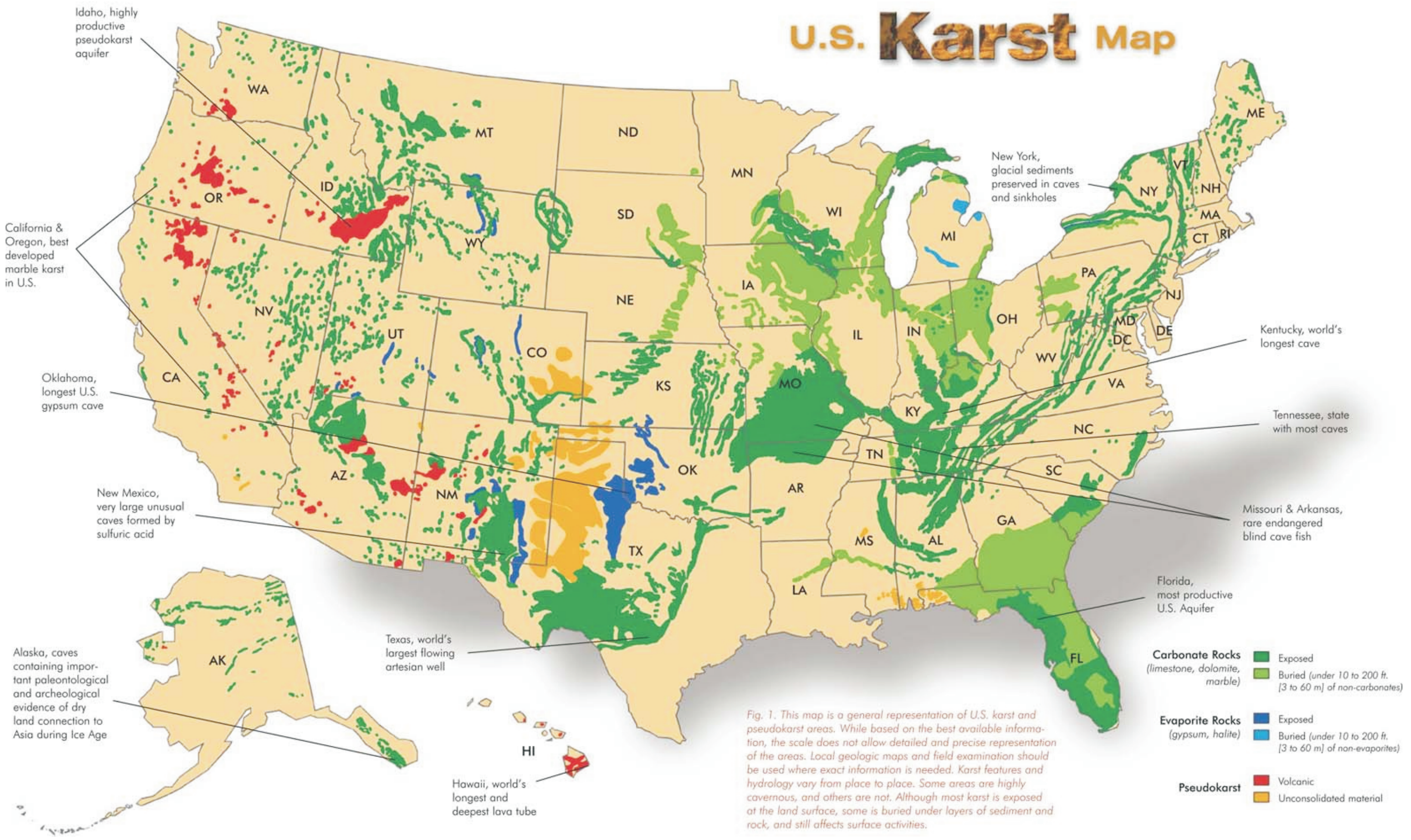


Figure 1: Watersheds of the Delaware River Basin. Source: Delaware River Basin Commission.



Idaho, highly productive pseudokarst aquifer

California & Oregon, best developed marble karst in U.S.

Oklahoma, longest U.S. gypsum cave

New Mexico, very large unusual caves formed by sulfuric acid

Alaska, caves containing important paleontological and archeological evidence of dry land connection to Asia during Ice Age

Texas, world's largest flowing artesian well

Hawaii, world's longest and deepest lava tube

New York, glacial sediments preserved in caves and sinkholes

Kentucky, world's longest cave

Tennessee, state with most caves

Missouri & Arkansas, rare endangered blind cave fish

Florida, most productive U.S. Aquifer

Fig. 1. This map is a general representation of U.S. karst and pseudokarst areas. While based on the best available information, the scale does not allow detailed and precise representation of the areas. Local geologic maps and field examination should be used where exact information is needed. Karst features and hydrology vary from place to place. Some areas are highly cavernous, and others are not. Although most karst is exposed at the land surface, some is buried under layers of sediment and rock, and still affects surface activities.

Figure 10: Karst map of the US published by AGI (Veni et al. 2001).

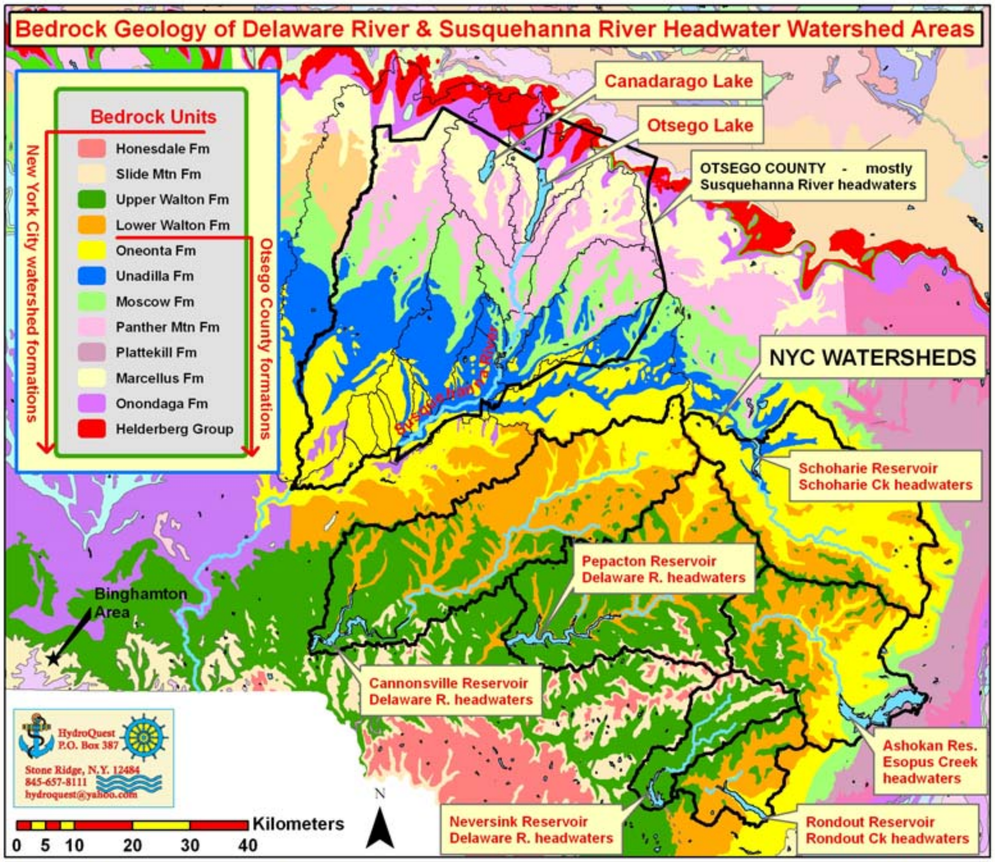


Figure 2: Bedrock geology of the headwater watershed areas of the Delaware and Susquehanna rivers prior to flowing into Pennsylvania. The bedrock geology is essentially the same in both areas and continues into PA. In some areas, some of the uppermost NYC watershed area formations have survived glaciation and erosion. [Geology synthesized from three NYS Museum databases.]

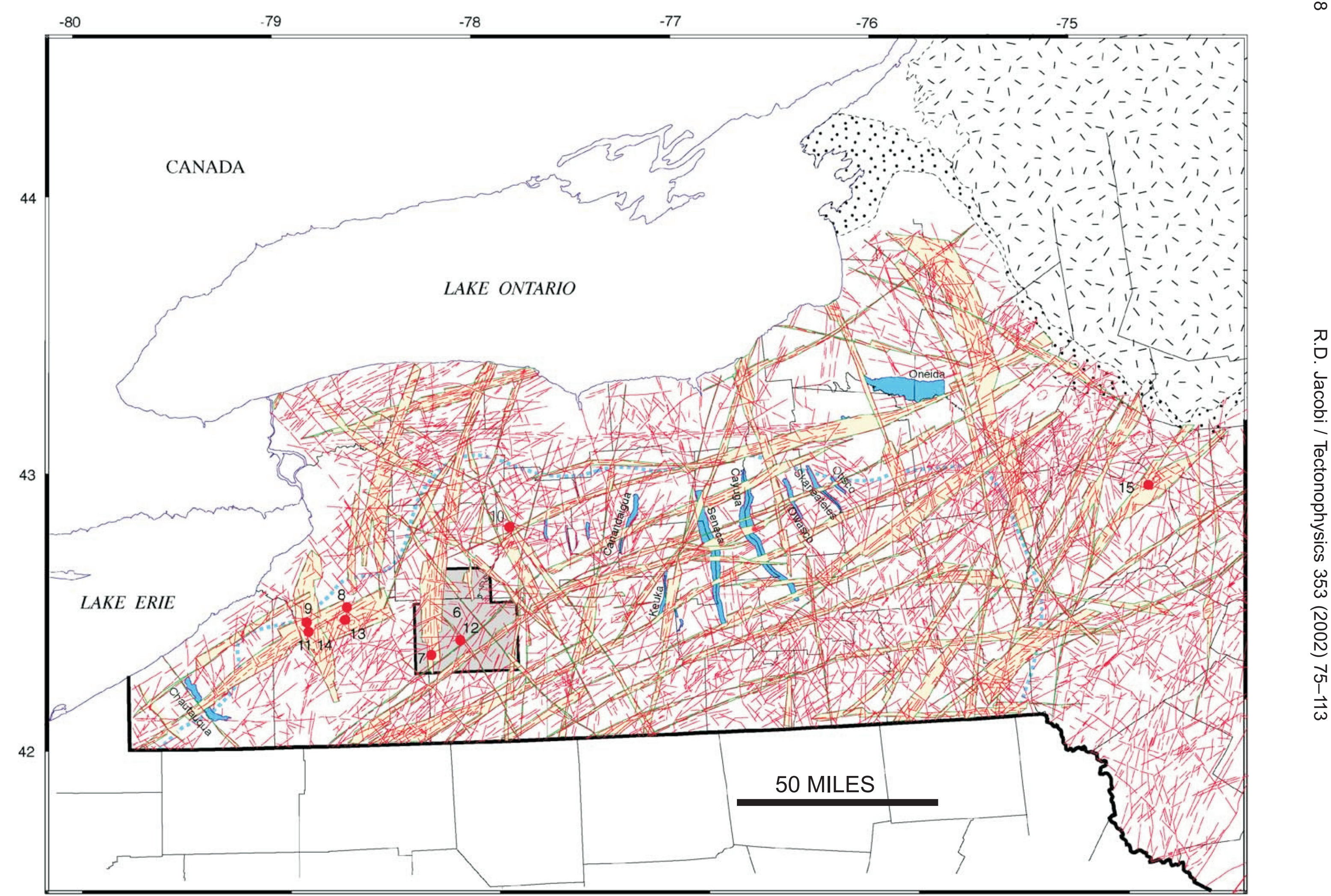
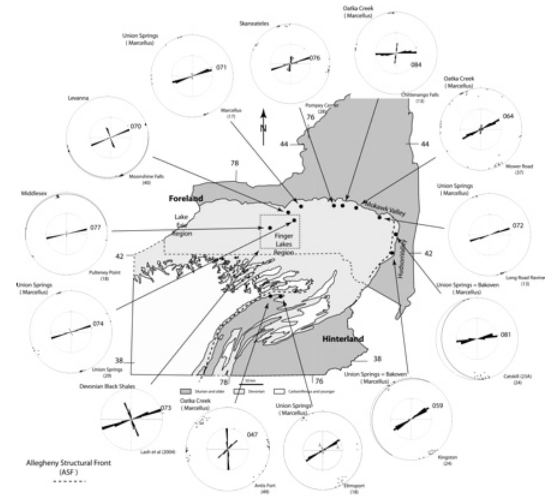
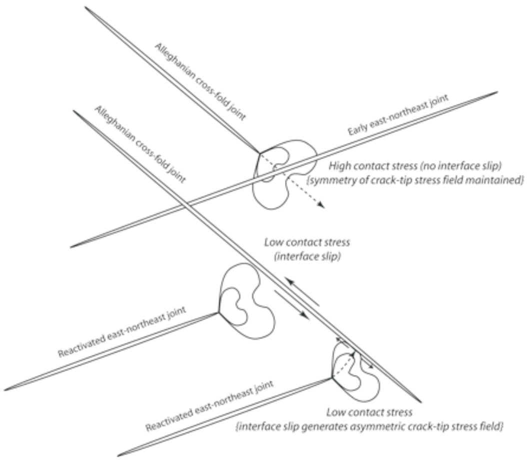


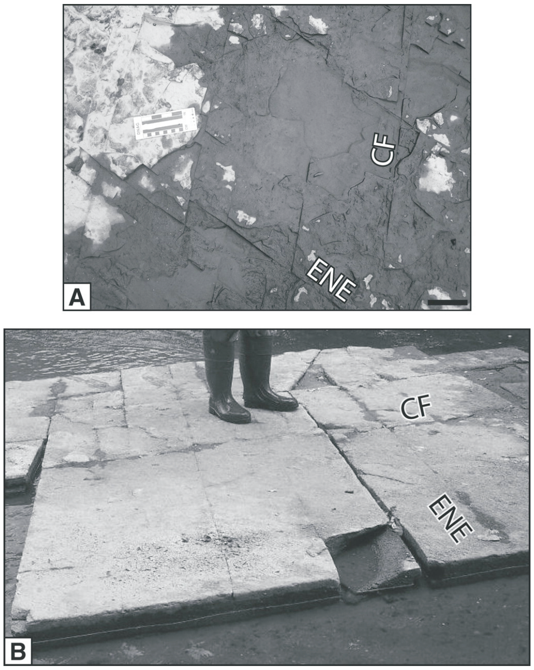
Figure 3: 1997 Landsat lineaments (red lines) as portrayed in Robert D. Jacobi's Figure 2 (2002). Lineaments and faults are widespread throughout the Appalachian Basin in New York State. These fractures and basement faults were examined via analysis of Landsat images, DEM data, aerial photography, side-looking aperature radar, hyperspectral imaging, soil gas anomalies, and field groundtruthing. Jacobi demonstrates that many of these features are seismically active. As portrayed above, many of these fractures are documented in the NYS portion of the Delaware River Basin where Jacobi conducted his geologic work. There is little doubt that similar mapping, if conducted in PA, would reveal similar fracture networks. These and other closely spaced fractures may provide pathways for upward methane and radioactive gas migration when encountered by vertical exploration wells or, later, after hydrofracturing. Similarly, high angle faults may provide upward pathways for pressurized, contaminant-laden, hydrofracturing fluids to reach freshwater aquifers.



From Engelder et al. (2009)



From Lash and Engelder (2009)



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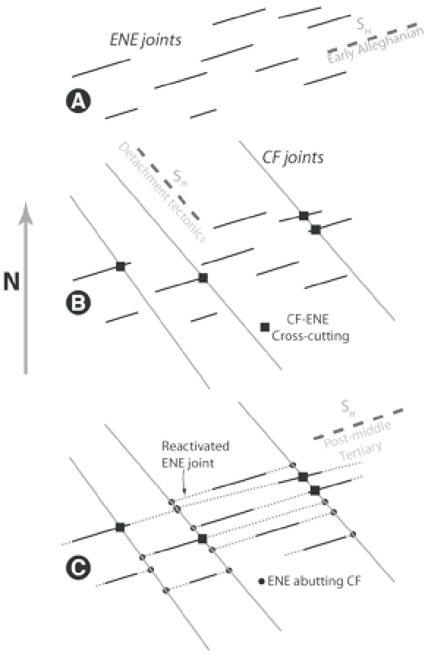


From Lash and Engelder (2009)

Figure 4. Figures from Engelder et al. (2009) and Lash and Engelder (2009) depict dominant joint orientations throughout the Appalachian Basin. Major joints strike east-northeast (J1 joint set) with younger cross-fold joints striking northwest (J2 joint set). The J1 joint set is more closely spaced and permeable than the J2 set. Exploration and other gas wells seek to intersect as many joint sets as possible, thereby maximizing productivity.

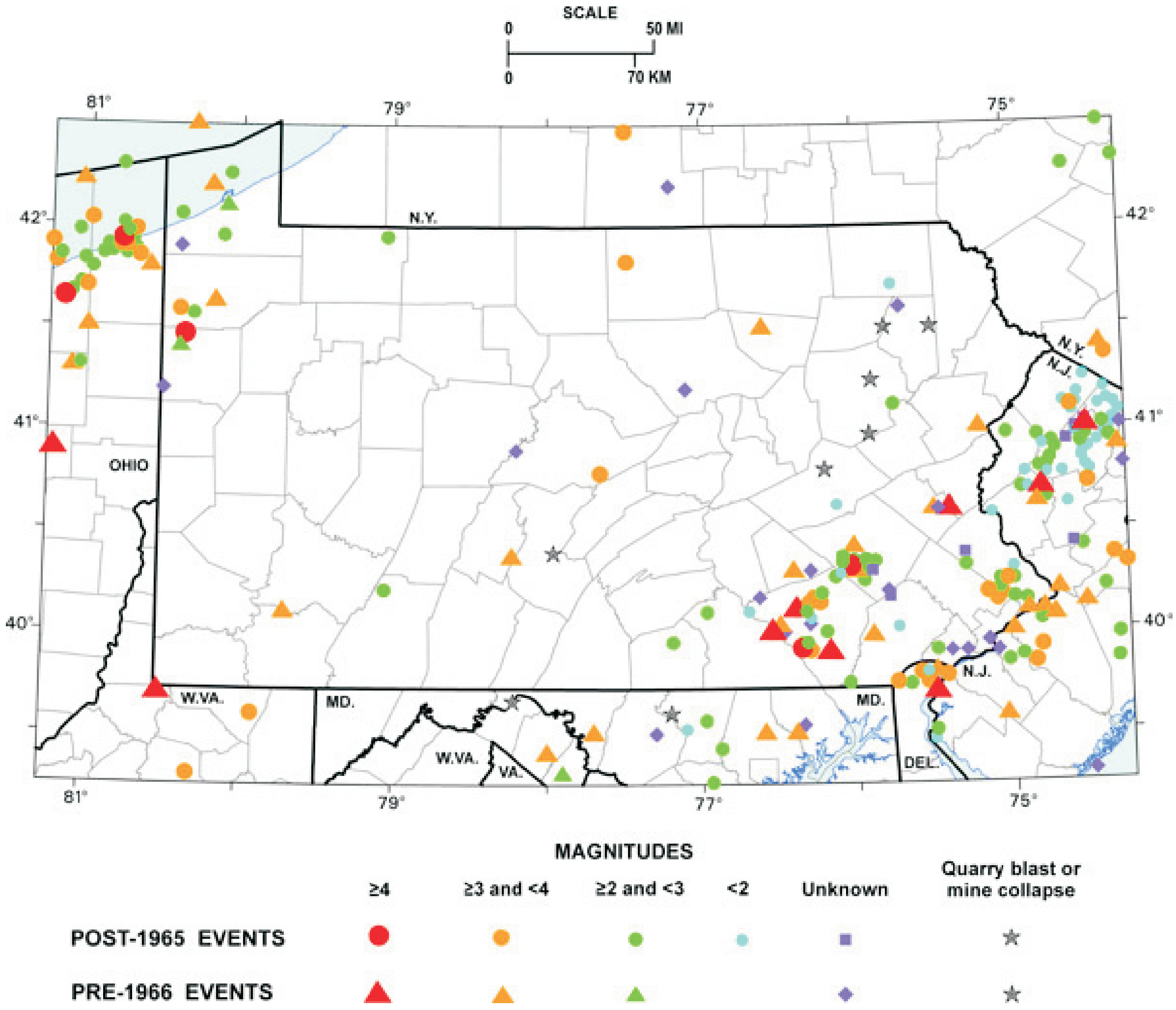
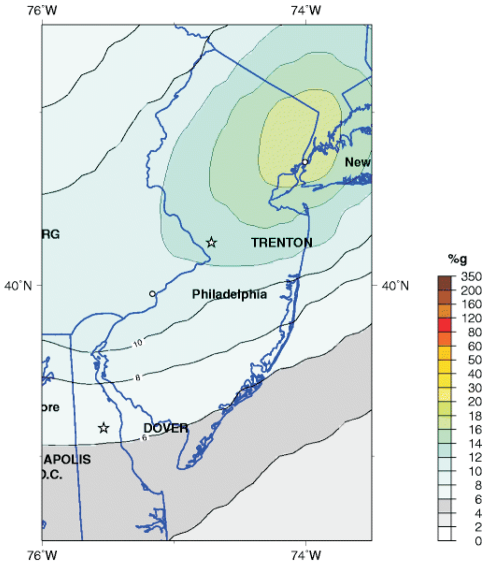
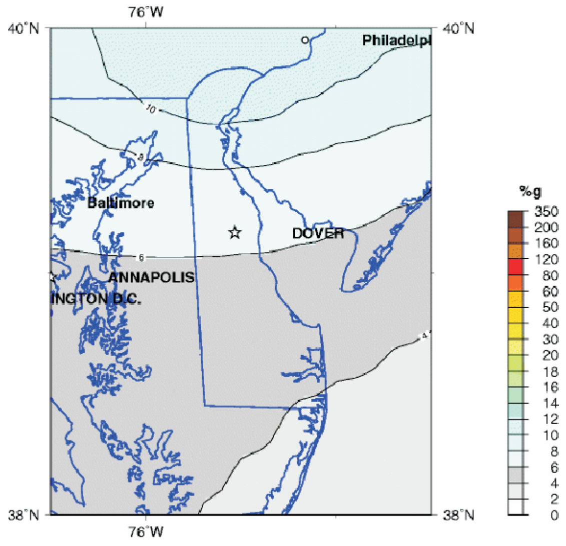


Figure 5: Earthquake epicenter map of PA and surrounding states showing the location of historical earthquakes. Source: PA Department of Conservation and Natural Resources. Compiled by geologist Rodger T. Faill using data through 7-31-03.



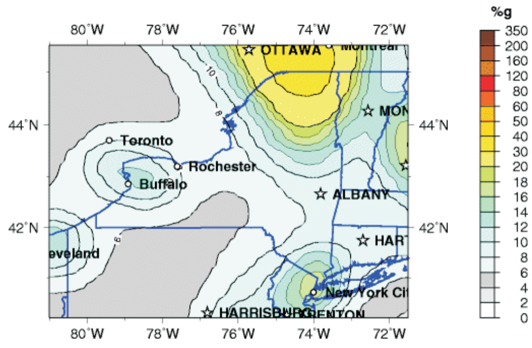
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project (2008)

New Jersey



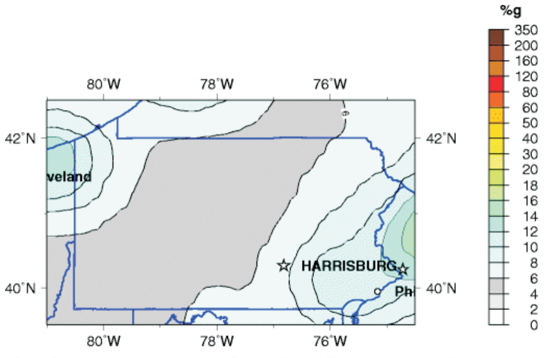
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project (2008)

Delaware



Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project (2008)

New York



Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project (2008)

Pennsylvania

Figure 6: Seismic Hazard Maps. Source USGS (2009). Earthquake Hazards Program.

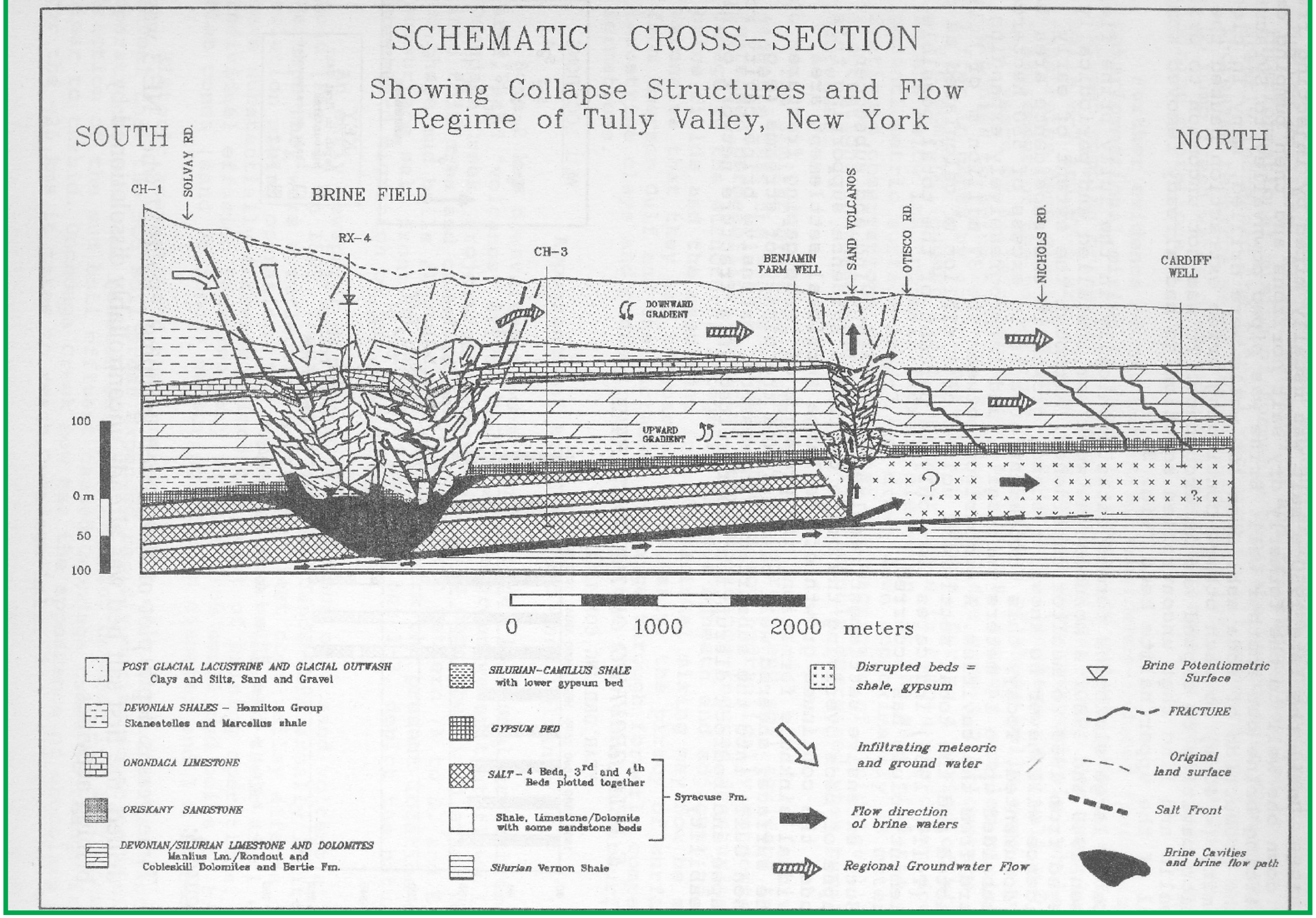


Figure 7: Structural collapse and anthropogenic alteration of a groundwater flow regime caused by solution mining, ground settlement, upward fracture propagation, and unnatural deep groundwater recharge from overlying freshwater aquifers (Fig. 2 of Rubin et al.). By analogy, hydraulic fracturing and chemical treatment of horizontal boreholes serves to integrate gas-rich shale beds by connecting joint sets, faults, and bedding planes over long distances. Upward expansion of even a small number of vertical fractures into overlying bedrock formations may result in a similar disruption and alteration of natural groundwater flow. Once this occurs, as in the Tully Valley example, plugging and abandonment of wells will do nothing to restore pre-existing aquifer and groundwater flow conditions.

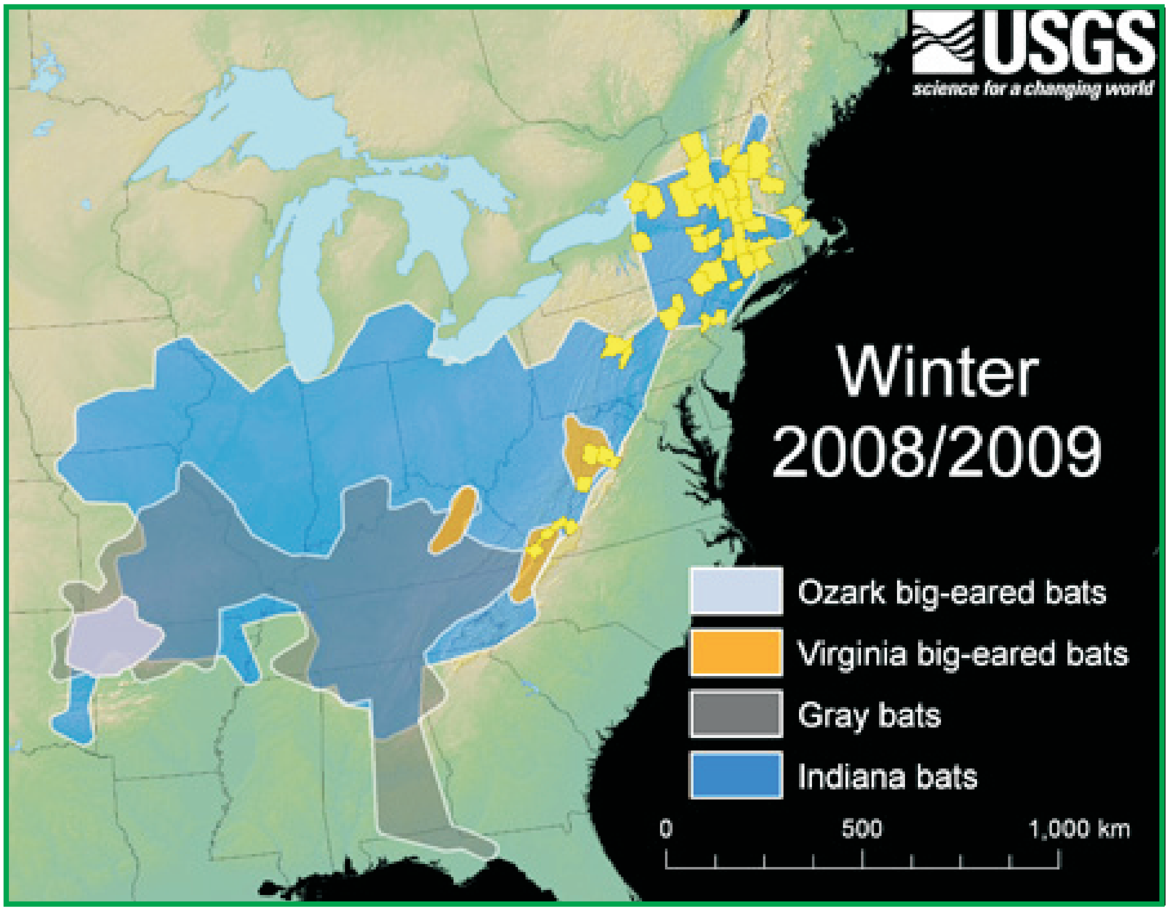
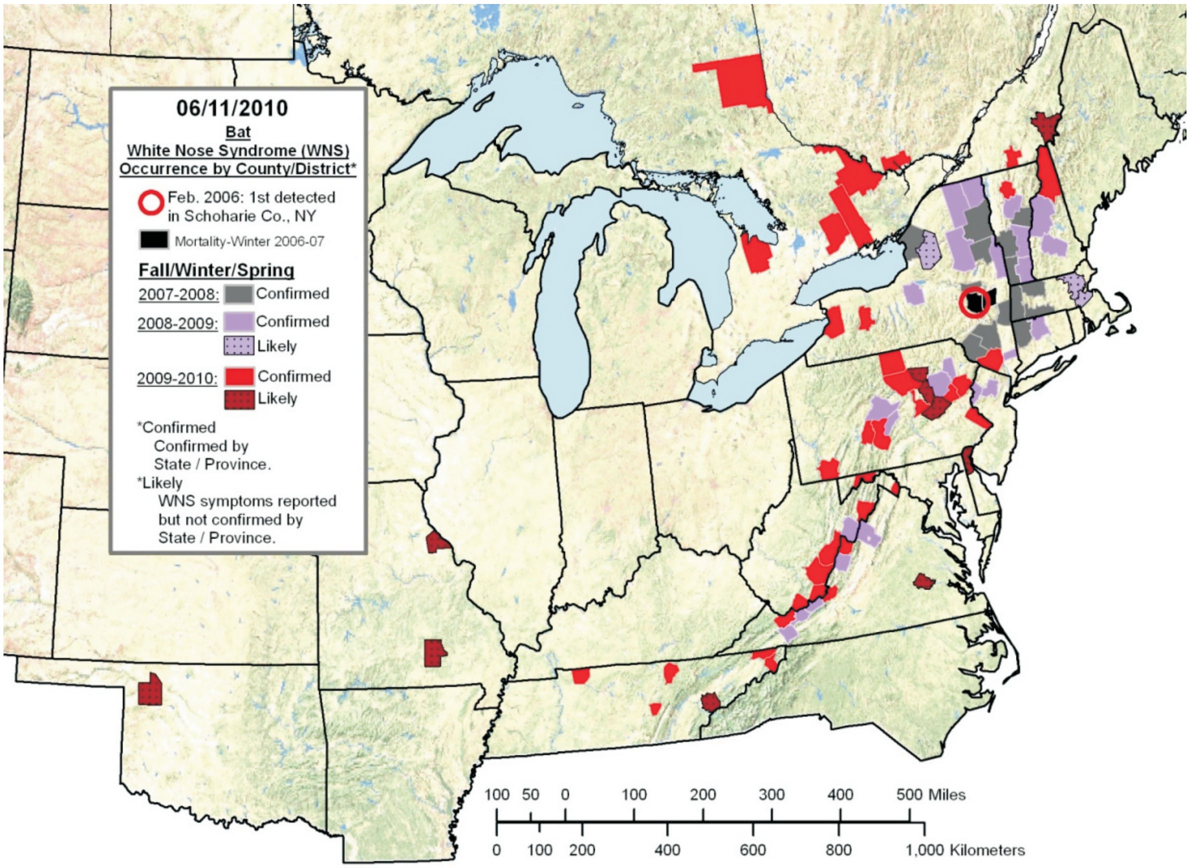
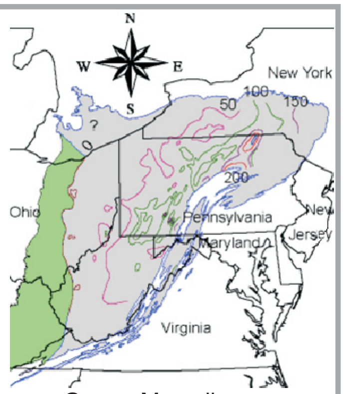


Figure 8: Map illustrating the ranges of endangered species of hibernating bats in the eastern U.S. A portion of the range of the endangered Indiana bat lies within the Delaware River Basin. Map data compiled by Cal Butchkoski, Pennsylvania Game Commission and presented in a USGS publication (White-Nose Syndrome Threatens the Survival of Hibernating Bats in North America; 2010).



Map by: Cal Butchkoski, PA Game Commission



Gray = Marcellus Shale: USGS

Figure 9: The spread of White-Nose Syndrome (WNS) in bats in the eastern U.S. Caves in the Delaware River Basin may have been adversely impacted by WNS. Methane and other gas field contaminants pose a potential risk to bat populations in caves situated above the Utica Shale. Map by Cal Butchkoski, PA Game Commission.