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Spatial and Temporal Characteristics of Historical Oil and Gas Wells in Pennsylvania: Implications for New Shale Gas Resources

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S *Supporting Information*

ABSTRACT: Recent large-scale development of oil and gas from low-permeability unconventional formations (e.g., shales, tight sands, and coal seams) has raised concern about potential environmental impacts. If left improperly sealed, legacy oil and gas wells colocated with that new development represent a potential pathway for unwanted migration of fluids (brine, drilling and stimulation fluids, oil, and gas). Uncertainty in the number, location, and abandonment state of legacy wells hinders environmental assessment of exploration and production activity. The objective of this study is to apply publicly available information on Pennsylvania oil and gas wells to better understand their potential to serve as pathways for unwanted fluid migration. This study presents a synthesis of historical reports and digital well records to provide insights into spatial and temporal trends in oil and gas development. Areas with a higher density of wells abandoned prior to the mid-20th century, when more modern well-sealing requirements took effect in Pennsylvania, and areas where conventional oil and gas production penetrated to or through intervals that may be affected by new Marcellus shale development are identified. This information may help to address questions of environmental risk related to new extraction activities.

■ INTRODUCTION

Recent large-scale development of oil and gas from low-permeability unconventional formations (e.g., shales, tight sands, coal seams) has raised concern about potential environmental impacts. Production from the Marcellus shale in the U.S. Appalachian basin alone has exceeded 15 billion cubic feet per day (0.42 billion cubic meters per day), with 5 trillion cubic feet (0.14 trillion cubic meters) annual production projected by 2022.[1] Historical production of natural gas and oil in Pennsylvania from more porous and permeable siliciclastic formations has resulted in the completion of hundreds of thousands of wells over the past 150 plus years, beginning with the Drake oil well in Titusville in 1859. Many of those wells were emplaced before modern oil and gas regulations and reporting requirements took effect.[2] These legacy wells, if left improperly sealed, potentially serve as pathways for unwanted migration of fluids associated with oil and gas drilling and production. Uncertainty in the number, location, and abandonment state of legacy wells hinders environmental assessment of exploration and production activity. The objective of this study is to apply available information on Pennsylvania oil and gas wells to better understand their potential to serve as pathways for unwanted fluid migration. This study presents a synthesis of historical reports and digital well records to provide insights into spatial and temporal trends in oil and gas development. This information may help to address questions of environmental risk related to new extraction activities.

Risk Considerations with New and Historical Oil and Gas Development. There is significant public concern that new unconventional oil and gas exploration and production could result in environmental damage to water and air resources. Much of that concern relates to potential impacts of uncontrolled fluid migration (e.g., brine, hydraulic fracturing fluids, natural gas, and oil) through the subsurface. Brine and fracturing fluid migration to fresh water aquifers would impair those resources.[3] Uncontrolled gas migration can lead to explosive conditions in near-surface environments (e.g., basements) and leakage to the atmosphere. One noteworthy area of debate about emissions from unconventional natural gas and oil emissions performance relates to discrepancies in assessed upstream (extraction and collection) emissions between "top-

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down" and "bottom-up" methodologies and uncertainty about the source of those discrepancies.[4−8] One source of fugitive emissions to the atmosphere that has not traditionally been accounted for in bottom-up inventory-based life cycle analyses is the migration of natural gas from the subsurface through pre-existing wells. Kang et al.[9] have extrapolated field measurements to estimate that abandoned oil and gas wells may have contributed between 4 and 7% of total anthropogenic methane emissions in Pennsylvania from 2010. Because new unconventional fossil resource production targets deep intervals, impactful fluid migration may be considered unlikely unless high permeability pathways for vertical migration of fluids are present. Dusseault and Jackson[10] have identified fracturing fluid migration through legacy wells during stimulation and buoyant migration of natural gas through poorly cemented wellbores as possible routes of fluid migration. Several studies have considered issues related to integrity of operational and plugged and abandoned wells,[11−16] including field investigation of unwanted fluid migration through subsurface pathways,[17−19] implications of leakage for environmental risk performance in oil and gas resource recovery, and geologic CO_2 storage settings.[20,21,12,22] Information on legacy oil and gas well completion and abandonment attributes and wellbore leakage performance has been used as the basis to rank well leakage potential;[23] those rankings can be applied to inform risk-based monitoring network design for improved leak detectability in carbon dioxide (CO_2) storage scenarios.[24]

Marcellus Shale: Geologic Setting. The Marcellus Formation is a Devonian age, organic-rich, natural-gas- and condensate-bearing shale interval in the Appalachian basin of the northeastern United States, covering an area of approximately 100 000 square miles (sq mi) (about 260 000 km^2) and ranging in thickness from as little as 40 ft (12 m) to nearly 900 ft (270 m). The depth of the Marcellus ranges from surface outcrops in New York, eastern and central Pennsylvania, and West Virginia to approximately 8900 ft (2700 m) in south central Pennsylvania. Areas targeted for recovery of economic resource in western Pennsylvania, for example, typically have thicknesses on the order of 50−200 feet (ft) (15−60 m) and occurring at depths varying from 4000 to 8500 ft (1200−2600 m).[25] The Middle Devonian Tully Limestone is commonly recognized as a geomechanical barrier to vertical fracture propagation, but anecdotal evidence suggests that this may not always be the case.[26−28] A figure illustrating the generalized stratigraphy of western Pennsylvania is shown in Figure 1.

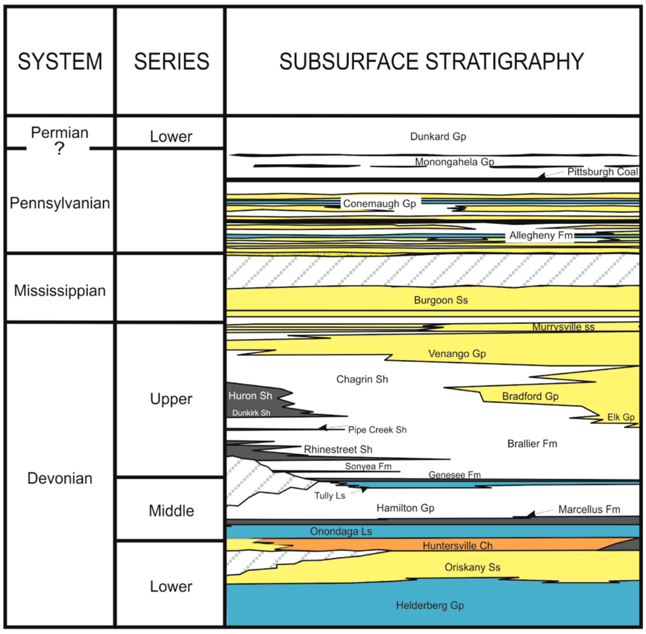

Figure 1. Extent of conventional oil and gas fields in the Commonwealth of Pennsylvania (modified from GIS data sets prepared by the Midwest Regional Carbon Sequestration Partnership).[46]

Pennsylvania Oil and Gas Well Regulation and Industrial Well Cementing Practice. Following is a brief discussion of historical industrial practice and regulation of oil and gas well in Pennsylvania. This discussion is not intended to be exhaustive but rather to highlight information relevant to the subject considered. Oversight of Pennsylvania's petroleum industry began in May 1891, when the first statute was passed requiring the plugging of abandoned wells although no method of plugging was prescribed. In 1921, new statutes were passed related to oil and gas development requiring casing of new oil and gas wells, prescribing that abandoned wells drilled through marketable coal seams be plugged with "well seasoned, round wooden plugs" and establishing penalties for mismanagement of oil and gas wells.[29] The Clean Streams Law (Pennsylvania Act 394) of June 1937 was enacted to protect and enhance the quantity and quality of water resources in Pennsylvania,[25,30] and has implications for petroleum development. On November 30, 1955, Act 225, the Gas Operations, Well-Drilling, Petroleum and Coal Mining Act, was passed to address standards for drilling oil and gas wells in areas colocated with coal mining.[25] This act also required drillers to register new oil and gas wells. The Oil and Gas Conservation Law (Pennsylvania Act 359) of July 1961 encouraged the efficient exploration and development of deeper oil and gas resources by establishing permitting, well-spacing requirements, and unitization for wells penetrating the top of the Middle Devonian Onondaga Limestone (or its stratigraphic equivalent) and drilled to a depth greater than 3800 ft (1160 m).[25] In December of 1984, the Pennsylvania legislature passed both the Coal and Gas Resource Coordination Act (Pennsylvania Act 214)[30] and the Oil and Gas Act (Pennsylvania Act 223).[31] The Coal and Gas Resource Coordination Act applies only to gas wells drilled in areas with workable coal seams and is designed to minimize disputes between subsurface mineral rights owners in situations where both resources are extracted. This Act was amended in May 2011 (now referred to as Act 2 of 2011) to address use of multiwell pads and other special concerns related to modern shale gas development. The Oil and Gas Act of December 1984 repealed Act 225 of 1955 to establish a more comprehensive regulation of the oil and gas industry in Pennsylvania, require reporting of the details of drilling and production activities, establish bonding requirements, and provide environmental safeguards to protect water resources and wetlands.[25,34]

The development of the modern petroleum industry can be related, in part, to the advent of effective well-cementing technology, with the first attempts at applying Portland cement for isolation reported in 1903, the first proven cementing system for zonal isolation invented in 1916, and the standardization of plugging procedures and cement composition by the American Petroleum Institute in 1952.[11,35,36] Considered together, this information suggests that the mid-20th century was a time of significant change in evolution of

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industry practice, regulation, and well-permitting requirements in Pennsylvania.[37,38,36,12]

Legacy Wells in Pennsylvania. Pennsylvania only began permitting new oil and gas wells in 1957; retroactive registration of older, previously undocumented wells was not required until the 1980s.[8] As a result, the record of wells drilled prior to 1957 is known to be incomplete. The total number of wells drilled in Pennsylvania has been estimated to range from 300 000 to 500 000 (300 000;[39] 325 000,[40] 350 000;[41] 350 000–500 000[9]). These wells are distributed throughout western Pennsylvania, as shown in Figure 2, but there is a significant subset of those wells that are not documented (where "documented" refers to wells for which there is a digital record in the Pennsylvania Internet Record Imaging System/Wells Information System (PA*IRIS/WIS) whether or not that record is complete) and for which location information is missing or inaccurate.[42]

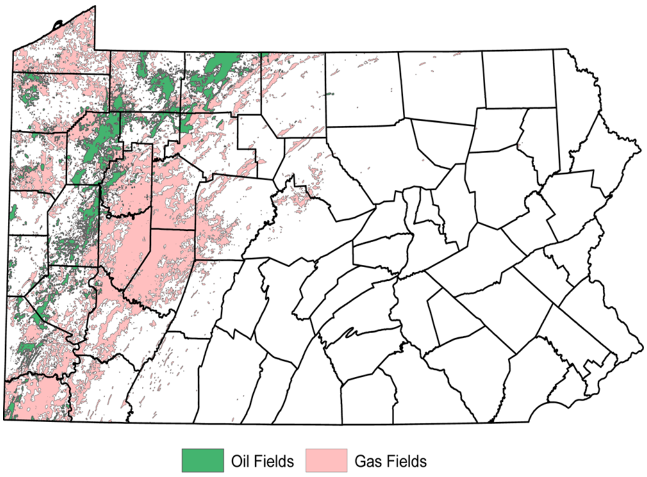

Figure 2. Generalized subsurface stratigraphy of western Pennsylvania's most commonly developed oil and gas producing formations.

The Pennsylvania Department of Environmental Protection (DEP) has an active program focused on locating and plugging orphan wells, i.e., inadequately plugged wells that have no identifiable owner or operator.[40] Furthermore, proposed regulation[42] would require Pennsylvania operators to identify the location of orphaned and abandoned wells that fall within a 1000 ft (305 m) buffer of new unconventional horizontal wells prior to hydraulic fracturing.

Locating Oil and Gas Legacy Wells. Site-scale evaluations and application of advanced well-finding technologies including geophysical and remote sensing techniques can resolve uncertainties about the location and density of legacy wells.[43,44,45] These approaches, however, can be labor intensive, limited by site access restrictions, and expensive to implement. This study uses available digital records and historical documents to explore trends in the density, completion year, and penetration depth of legacy wells in Pennsylvania. The data and methods described herein provide a framework that can be used to update these characterizations as new information becomes available, so to help improve risk characterization in areas of new oil and gas development.

■ MATERIALS AND METHODS

Estimating Number and Type of Historical Wells. Information on well count, well type, location, and depth of penetration was taken from publicly available sources. PA*IRIS/WIS[47] contains information about documented wells including location information, drilling and completion reports, plugging data, and geologic data. This state-supported database represents the most complete and internally consistent available digital data record of documented wells in Pennsylvania and was, therefore, used to describe the number, spatial distribution, density, and penetration depth for wells evaluated by this study.

The population of wells completed in Pennsylvania prior to 1957 is not documented as thoroughly as those completed since then. Therefore, we deferred to historical reports to locate and describe these older wells. Specifically, for the years 1859 through 1929, data compiled by Arnold and Kemnitzer[48] served as the primary source of information on well completion and spatial distribution (with data aggregated to the oil and gas district level as defined in Table SI-3). These data were manipulated to estimate the fraction of wells of each type (oil, gas, and dry) completed in each year in Pennsylvania and their spatial distribution (at the oil and gas district or county level). Well completions in Pennsylvania through 1928 were estimated to be 134 753 oil wells, 4079 natural gas wells, and 29 441 dry wells (for a total of 168 273 wells). For years after 1929, records from three primary sources were used: Oil Weekly annual activity reports, Minerals Yearbooks,[49] and PA Division of Oil and Gas Annual Reports (various years). These sources break out well reporting into a variety of coarse geospatial groupings (by county, field, and/or district) and different well type (oil, gas, dry, water input, and failure), such that some interpretation was required to estimate well counts (as detailed in the Supporting Information). When multiple records were indicated for a single year, the largest value was used.

Spatial information from registered wells (completed after 1956) was combined with both coarse spatial information from historical records and known extent of oil and gas fields[47] to estimate spatial density throughout the Commonwealth. A detailed description of data manipulations performed to arrive at well count and spatial distribution characterization is provided in the Supporting Information.

Table 1. Summary of Pennsylvania Well Completions As Estimated Based on Historical and Modern Digital Records

	oil well completions	gas well completion	dry well completions	total
historical completions through 1956	172750	11720	31936	216398
PA*IRIS/WIS completions (1957 and beyond)	38732	63010	12412	114154
total completions	211482	74730	44348	330560

Estimating Well Operational Life and Abandonment Year. It is presumed that a well's state of abandonment, i.e., its integrity as an effective barrier to unwanted fluid migration, roughly corresponds to its year of abandonment. For the analysis presented herein, it has been assumed that wells abandoned earlier than 1957 are likely to have been improperly abandoned (i.e., not meeting plugging standards sufficient to prevent unwanted fluid migration) because of prevailing oil and gas industry practices[50] and limited regulation of well plugging at the time.[29−33] Even so, information on the year of well abandonment is poorly documented for older wells. Therefore, estimated well operational life was added to well completion

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year to arrive at an estimated abandonment year for the well data evaluated in this study. Operational life of individual wells was treated as an uncertainty, and appropriate distributions were assigned for primary oil, secondary oil, and natural gas wells as described in Table 2.

Table 2. Definition of Distribution for Well Operational Life by Well Type

well type	estimated production life distribution (years)	cistribution P_{10}, P_{50}, P_{90} (years of operation)
oil well, primary production	uniform, 10−20	11, 15, 19
oil well, secondary production (water flood)	uniform, 10−30	12, 20, 28
gas well	truncated lognormal; 30, 10, 1, 90 (mean, standard deviation, minimum, maximum)	18.8, 28.5, 43.1
dry well	0	N/A

Oil fields in some parts of Pennsylvania (particularly those in the Bradford district) are known to have been extensively water-flooded after primary production, which significantly extended the economic life of those wells.[51] Oil wells in the Bradford district were therefore considered to have longer operational life than oil wells in other parts of the state, which typically only experienced primary recovery. Dry wells were assumed to be abandoned in the year of completion, so production life was estimated to be zero for these wells and abandonment year taken to be equivalent to completion year. Median (P_{50}) and 80th percentile confidence bounds (P_{10} and P_{90}) for oil and gas well operational life were used as the basis to calculate confidence bounds for abandonment year of wells completed before 1957 and to estimate the fraction of wells of each type that may be expected to be abandoned to pre-1957 standards.

Characterizing the Thickness of Undisturbed Overburden Barrier. Potential for fluid migration to overlying receptors will be a function of the thickness of the undisturbed interval between the stimulated reservoir and anthropogenic leakage pathways (e.g., wellbores). Spatial data were interpreted to understand trends in the thickness of the undisturbed interval between historical oil and gas exploration and the Marcellus Formation in Pennsylvania. Pennsylvania's Onondaga Limestone isopach[46] was used as a reference point for the bottom of the Marcellus Formation. The thickness of undisturbed interval above potential Marcellus extraction activity was calculated as the difference between the depth at the top of the Onondaga Limestone and the depth of the deepest well in each 1 km^2 pixel in the study domain. Negative undisturbed interval thicknesses represent those pixels where historical well bores penetrate through the top of the Onondaga Limestone (and therefore through the Marcellus Formation). Calculated undisturbed interval thicknesses for each pixel were binned into one of four categories (as illustrated in Figure 3): (1) those that penetrate through the top of the Onondaga Limestone, (2) those that penetrate to within 500 ft (152 m) of the top of but not through the Onondaga Limestone, (3) those that penetrate to between 500 and 2000 ft (152−610 m) of the top of the Onondaga Limestone, and (4) those that do not penetrate to within 2000 ft (610 m) of the top of the Onondaga Limestone. Wells that reached the Onondaga Limestone fully penetrate the overlying Marcellus Formation and, therefore,

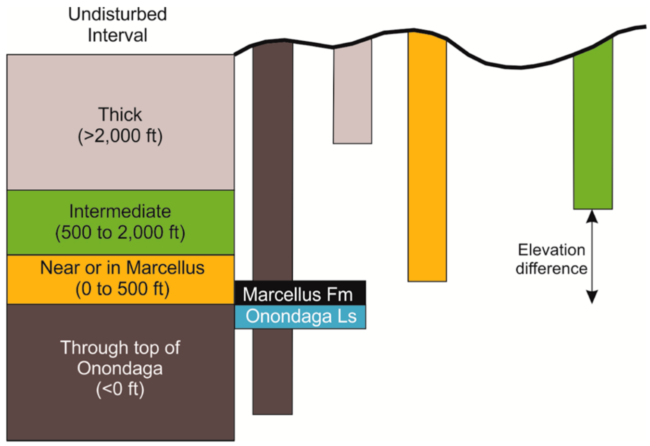

Figure 3. Simplified schematic illustrating the meaning of calculated undisturbed interval thickness between deepest vertical oil and gas well and top of the Onondaga Limestone. Interval bins and color scheme correspond to those in the histogram in Figure 5 and the raster pixel colors used in the map in Figure 4.

represent a significant potential pathway for unwanted fluid migration from new Marcellus development. Similarly, wells that penetrate to a depth of less than 500 ft (152 m) from the top of the Onondaga Limestone likely lie within the Marcellus Formation or in a zone that would be hydraulically connected with the Marcellus as a result of Marcellus shale gas well stimulation.[27] Areas with wells that fall between 500 and 2000 ft (152−610 m) above the top of the Onondaga Limestone are considered less likely to be, but still potentially, impacted by hydraulic fracturing activity in the Marcellus because some incidence of fractures reaching to nearly 2000 feet have been observed.[27,28] Areas with wells that do not reach to within 2000 ft (610 m) above the top of the Onondaga Limestone are expected to generally present less risk for unwanted fluid migration because of the thicker undisturbed interval between the well and potential hydraulic fracturing activity.

RESULTS AND DISCUSSION

Estimate of Number of Well Completions in Pennsylvania. Using information on the number of legacy wells as reported in historical records and digital databases of more recent well completions, it is estimated that the total number of oil and gas wells in Pennsylvania as of October 21, 2012 is approximately 330 000. Table 1 provides a summary of the count of oil, gas, and dry wells, as estimated from historical records and PA*IRIS/WIS. On the basis of these numbers, the majority of conventional well completions in Pennsylvania are oil wells, and most wells were completed prior to 1957. A Bayesian posterior interval analysis was used to consider the credible interval around the total well count given the five available estimates mentioned above (four previously reported well counts and a fifth developed herein). On the basis of assumptions of noninformative prior (Jeffreys' Rule) and normally distributed prior and posterior, an estimated 95% credible interval for the posterior mean of between about 305 000 and 390 000 wells was calculated, an estimate that can be updated as more information becomes available in the future.

Spatial Distribution and Abandonment Characteristics of Oil and Gas Wells. Well count, well type, and available information on spatial distribution of wells was used as

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the basis to estimate spatial density of oil and gas wells completed before 1957. Available information on the spatial distribution of wells was much more limited than that in modern records; however, the resulting maps provide useful insight into regional spatial trends. It is important to note that these maps should not be used as the basis for site-scale evaluation. On the basis of the spatial analysis, general ranges of pre-1957 well completion spatial density are estimated to be about 0.5−1 natural gas wells per square kilometer (wells per km^2) (1.3−2.6 per square mile; wells per mi^2) in areas of natural gas development; about 28−62 oil wells per km^2 (73−161 wells per mi^2) in areas of oil development; and about 1−2 dry wells per km^2 (2.6−5.2 per mi^2) in areas of oil and gas development. In areas with both oil and gas production, the wells were summed to determine densities. Maps of spatial distributions and details of their derivation are provided in the Supporting Information.

Table 3 summarizes the estimated number of wells of each type that were abandoned before 1957, i.e., the year in which

Table 3. Estimated Fraction of Wells Completed before 1957 That Were Also Abandoned before 1957

	estimated count − wells completed before 1957	fraction abandoned before 1957 (95% confidence interval)
oil wells with primary production life only	133235	93−97%
oil wells with primary and secondary production life	39496	28−49%
gas wells	11535	0−49%
dry wells	31889	100%

well-plugging practices became regulated in Pennsylvania. On the basis of the assumption that dry wells are abandoned in the same year in which they are drilled and the analysis assumption that wells abandoned before 1957 are improperly abandoned, it is estimated that all dry wells completed before 1957 are improperly abandoned. Nearly all oil wells in Pennsylvania that saw only primary production are expected to have been abandoned before 1957 whereas less than half of the oil wells that experienced both primary and secondary production are expected to have been abandoned before 1957. Up to one-half of all historical natural gas wells completed before 1957 are estimated to have been abandoned before 1957.

The areas with the highest concentration of total wells estimated to have been abandoned before 1957, i.e., densities > 10 wells per km^2, lie primarily in western Pennsylvania (Figures 4 and SI-4 through SI-8). A density threshold of 10 wells per km^2 (28 wells per mi^2) is considered a high well density that is representative of areas of significant oil and gas development;[22] this threshold is used herein to facilitate discussion. It should be noted that although a higher well density will correspond to greater statistical chance of experiencing impacts from poorly abandoned legacy wells even a single poorly abandoned well could potentially provide a conduit for fluid migration that could result in impact to the environment or human health. For example, in one case, hydraulic fracturing at a shale gas well in Tioga County, Pennsylvania, resulted in ejection of natural gas and brine from a nearby legacy well to a height of 30 ft (9 m) for more than a week.[39]

Thickness of Undisturbed Interval above the Marcellus. The histogram in Figure 5 shows the distribution of smallest undisturbed intervals in each of 26 603, 1 km^2 (0.39 mi^2) pixels. About 65% of pixels in Pennsylvania's oil and gas fields (about 17 000 km^2) have greater than 2000 ft (610 m) of undisturbed interval, but 30% of pixels (about 8000 km^2 of area) have vertical wells that penetrate to within 500 ft (152 m) or less of the Onondaga Limestone and therefore may be considered to represent an increased risk of fluid migration.

Much of northwestern Pennsylvania has vertical legacy wells that penetrate through the top of the Onondaga Limestone (which becomes shallower toward the northwestern corner of the state) and therefore represents a region with significant potential for unwanted fluid migration from stimulated Marcellus shale gas wells (Figure 4). Additionally, there are other isolated areas in Pennsylvania where wells have penetrated the Onondaga Limestone (not clearly visible at the scale of Figure 4). Even so, as the Marcellus Formation becomes shallower in northwestern Pennsylvania, it is less likely that it will be targeted for natural gas production because subsurface stress conditions limit the effectiveness of hydraulic fracturing a horizontally drilled well. Engineered hydraulic fractures are tensile fractures that propagate in a direction perpendicular to the least principle stress. In portions of a formation where the overburden (vertical) stress is greatest (and therefore, the horizontal stress is least), fractures will propagate vertically; in cases where overburden stresses are less than the maximum horizontal stress, i.e., depths of about 2000 ft (610 m) or less, fractures will propagate horizontally.[52,53] This suggests that Marcellus development in the area where the Marcellus is relatively shallow (northwest of the 2000 ft (610 m) Onondaga contour line shown in Figure 4) may be limited. Inspection of Marcellus well-completion trends supports that observation.[47,54]

Implications for Regional Investigation: Venango County. This state-scale assessment highlights several areas that warrant more detailed consideration for county- or site-scale data mining and/or ground investigation. One such area is the northern portion of Venango County, including Oil Creek State Park where Edwin Drake struck oil. This is an area with a high concentration of legacy wells abandoned before 1957 as well as existing wells that penetrate the Onondaga Limestone.

In the Oil Creek State Park area (Figure 6A), PA*IRIS/WIS identifies a total of 296 wells: 44 gas wells were drilled to an average of 1800 ft (550 m) below the Marcellus (range of 1400−2000 ft, or about 430−610 m) with an average completion year of 2000 (range: 1989−2010), 248 pre-1957 oil wells, 93 of which have a completion year of 1900 or earlier (with some having no completion date listed), and four dry wells. It is likely that many more wells were drilled in this area during the oil boom of the 1860s than those that are recorded in the digital record (as documented by this study). The cross section (Figure 6B) shows the penetration depth of documented wells that fall within 330 ft (100 m, orthogonal distance) of the transect line. The natural gas wells recently drilled to the west are less densely spaced than the wells in the oil fields to the east, but those oil wells are notably shallower and therefore much less likely to represent a significant pathway for fluid migration from stimulation of Marcellus shale gas wells. There is, however, some area of overlap where both deep and shallow wells are located. Although not in the scope of this study, site-specific evaluations are recommended for future field characterization and modeling work.

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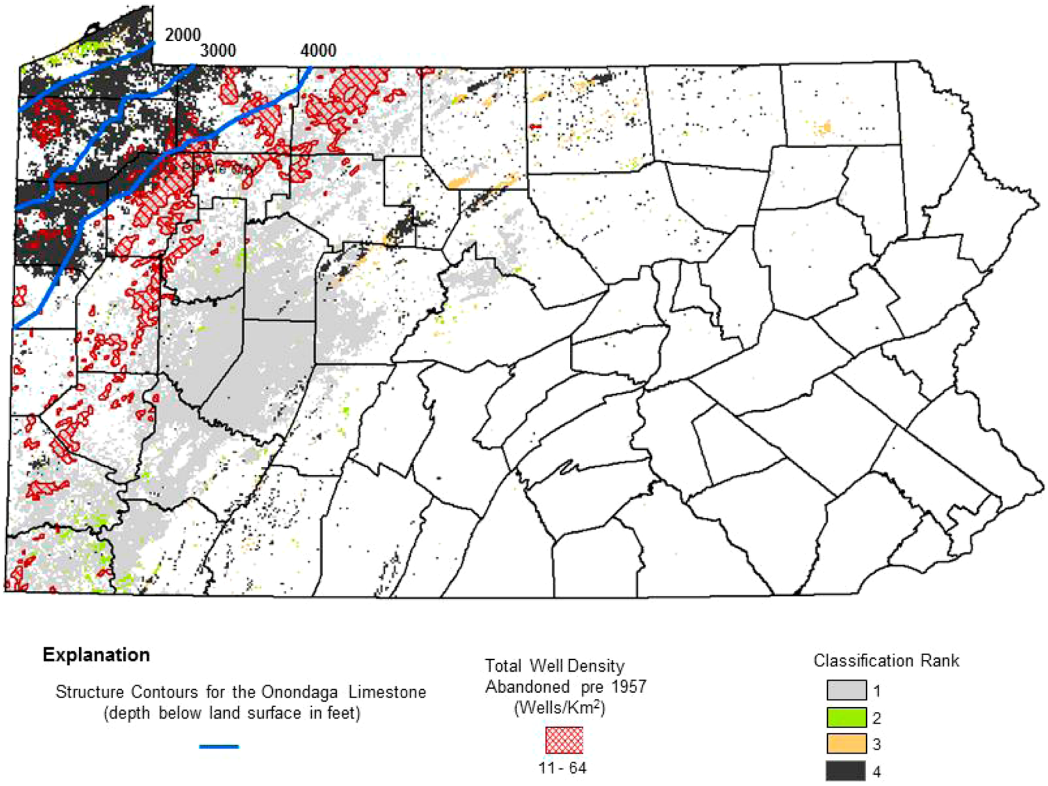

Figure 4. Thickness of undisturbed interval between top of Onondaga Limestone and bottom of deepest well (per 1 km^2 pixel) greater than 2000 ft (610 m; light gray), between 2000 and 500 ft (610 and 152 m; green), between 500 and zero ft (152 and 0 m; orange), and where the deepest wells penetrate through the top of the Onondaga (dark gray); areas with greatest expected density of wells abandoned before 1957 (red hashed area representing well density 11−64 wells per km^2, or 28−170 wells per mi^2); generalized contours of depth to Onondaga Limestone illustrates areas of northwestern Pennsylvania where the Marcellus shale is relatively shallow.

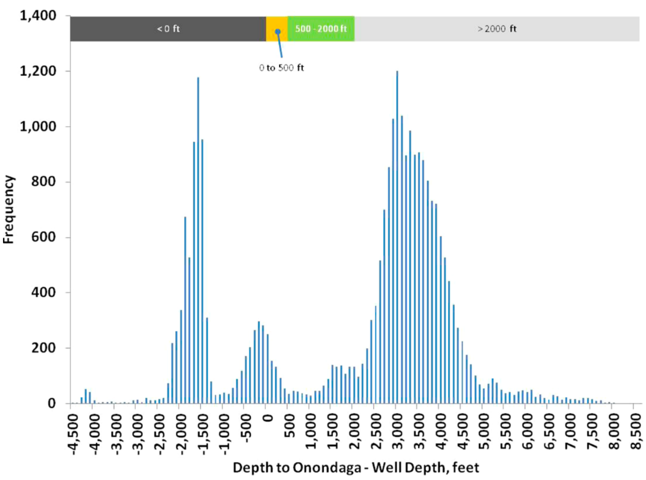

Figure 5. Distribution of undisturbed intervals (elevation difference between the deepest well and the top of the Onondaga Limestone in each analysis pixel). The top panel shadings correspond with categories of undisturbed interval thickness: thick (>2000 ft; > 610 m), intermediate (500−2000 ft; 152−610 m), thin (0−500 ft; 0−152 m), and wells that penetrate the top of the Onondaga (<0 ft).

■ IMPLICATIONS

The location, abandonment status, and depth of historical wells remain uncertain. However, this study has synthesized historical data to constrain the magnitude of historical activity and identify areas particularly worthy of scrutiny during the planning stages of hydraulic fracturing activity, i.e., areas with a high density of historical wells completed near or in the Marcellus Formation. These constraints can aid in improving our planning and management efforts. As an example, we can consider the recently reported emissions estimates from Kang et al.[9] That work considers uncertainty in the range of legacy wells contributing methane emissions to the atmosphere, using mean methane emissions from 19 measured well locations of 0.27 kg (0.60 pounds) of methane per well per day and an estimate of 300 000−500 000 abandoned and orphaned wells in Pennsylvania. A revised estimate of total wells (95% credible interval bounds of 305 000 and 390 000 wells) suggest that fugitive gas emission estimates may be in the lower range of that estimated by Kang and colleagues. Information on the location and spatial density of wells that are abandoned earlier may have value to help focus efforts to address issues of fugitive emissions and other unwanted fluid migration through these pathways.

The areas with the largest number and density of historical wells lie in regions of oil extraction. Well densities in regions of oil extraction can be expected to be more than an order of magnitude greater than those of gas fields, with the greatest well densities estimated to be more than 160 wells per km^2 (410 wells per mi^2). Preliminary estimates of well abandonment years suggest that of those wells completed prior to 1957 oil wells that experienced secondary water-flooding and natural gas wells are less likely to be improperly abandoned than dry wells and oil wells that had only primary production.

These results provide insight on general spatial and temporal trends in well attributes that can inform more focused, site-scale assessments and ultimately provide constraints to focus

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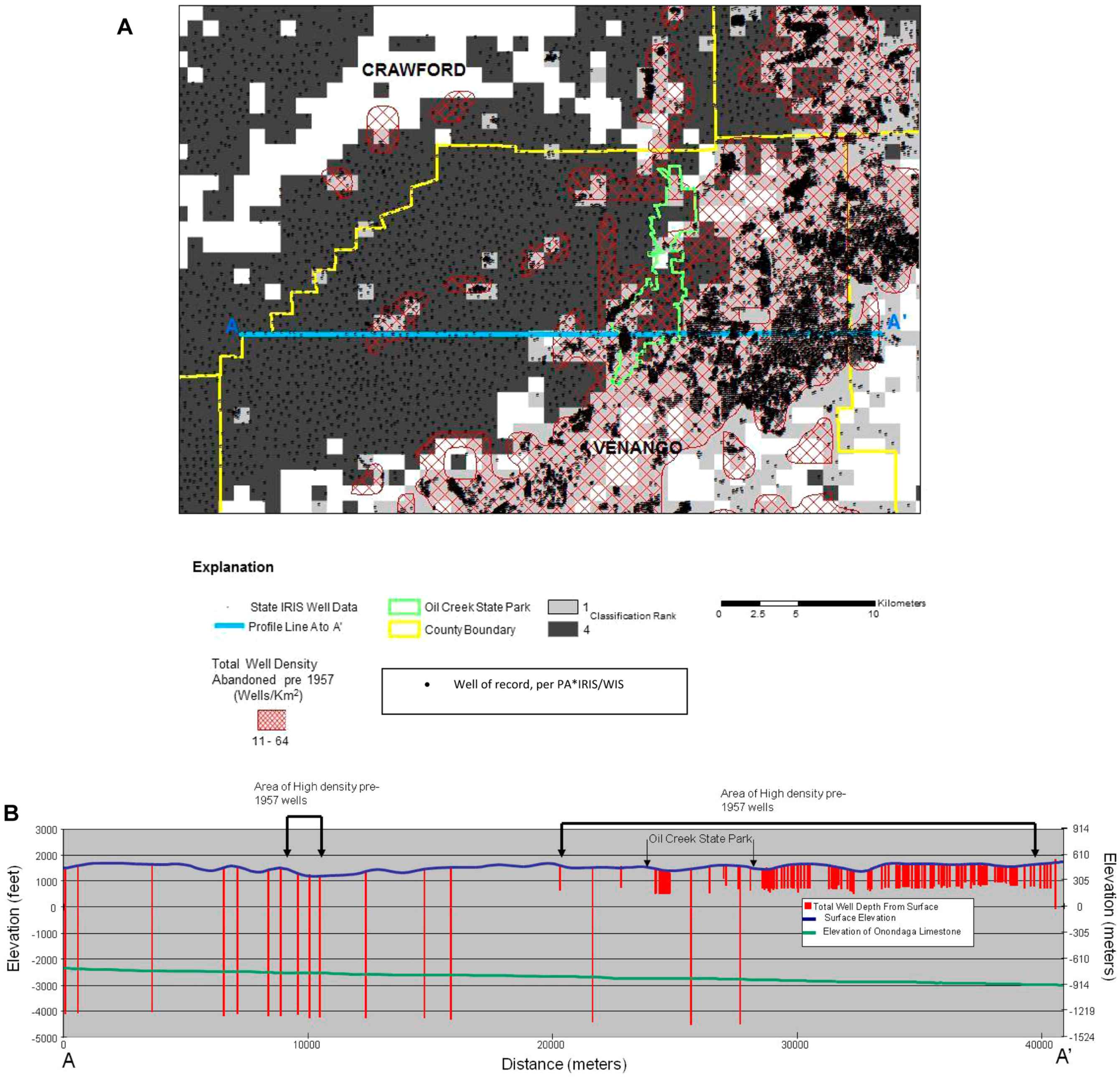

Figure 6. (A) Oil Creek State Park (green outline). Cells (1 km^2; 0.39 mi^2) with one or more wells penetrating to within 500 feet (152 m) of or through the Onondaga Limestone are shown in dark gray; PA*IRIS/WIS well locations are shown as black dots. Red cross-hatched region shows areas with wells abandoned prior to 1957 at estimated spatial densities between 11 and 64 wells per km^2 (28−170 wells per mi^2). (B) Cross section showing total well depth for all wells within 330 ft (100 m) of line A−A′ on panel A.

quantitative assessments of environmental risk in areas of current and future hydrocarbon development. Moreover, the data and methods are organized in a framework that easily allows revision of these estimates as new information becomes available. Finally, the framework can be applied to shale-gas-producing intervals in the Appalachian basin as well as other basins experiencing shale gas activity.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b00820.

Additional information providing detail on the methodology, data manipulation, and results of well number and density estimation. (PDF)

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Notes

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