Proximity of Precambrian basement affects the likelihood of induced seismicity in the Appalachian, Illinois, and Williston Basins, central and eastern United States

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ABSTRACT

A dramatic seismicity rate increase in the central and eastern United States (CEUS) over the past decade has been largely associated with the increase in enhanced oil and gas recovery operations and change in industry practices. However, certain areas of the CEUS that have experienced large increases in oil and gas operations, such as the Bakken and Marcellus Shale plays (Williston and Appalachian Basins, respectively), have very little (if any) induced seismicity. No prior study has adequately explained the occurrence or absence of induced seismicity on a regional, basin-to-basin scale in the CEUS. In this study, we improve the basement depth characterization and induced seismicity detection for the Appalachian, Illinois, and Williston Basins to determine whether the proximity of wastewater disposal and/or hydraulic fracturing to the crystalline basement increases the likelihood of induced seismicity. We also investigate the lithologic characteristics of sedimentary strata situated between injection intervals and the crystalline basement to evaluate the role they may play in diminishing the transmission of pore pressure during well stimulations. We find that wastewater disposal in basal sediments or hydraulic fracturing operations <1 km from the Precambrian basement raise the likelihood of induced seismicity, an observation that is consistent with the apparent absence of induced seismicity related to production from the Bakken and Marcellus Shale plays.

INTRODUCTION

The increase in enhanced oil and gas recovery operations and change of industry practices are now thought to be largely responsible for a dramatic rise in seismicity in the central and eastern United States (CEUS) over the past decade (e.g., Ellsworth, 2013; McGarr et al., 2015). While it is relatively rare for fluid injection to induce felt seismicity (typically M ≥ 3), there have been several cases over the past half century that identify strong relationships between injected fluids and seismicity (e.g., Healy et al., 1968; Nicholson and Wesson, 1990; McGarr et al., 2002; Evans et al., 2012; Skoumal et al., 2014). Felt earthquakes as a result of hydraulic fracturing (HF) appear to be less common than those from wastewater disposal (WD) (e.g., NRC, 2013), but the number of documented cases of seismicity induced by HF activities has increased considerably over the past few years (e.g., Holland, 2013; Clarke et al., 2014; Skoumal et al., 2015a, 2015c, 2015a, 2016a; Atkinson et al., 2016; Atkinson et al., 2016; Bao and Eaton, 2016).

Arkansas, Colorado, New Mexico, Ohio, Oklahoma, and Texas have recently experienced elevated levels of seismicity near active oil and gas operations, with many studies demonstrating that a large proportion of these events were induced (e.g., Horton, 2012; Keranen et al., 2013; Kim, 2013; Rubinstein et al., 2014; Skoumal et al., 2015c; Frohlich et al., 2016). However, certain areas of the CEUS that have experienced large increases in oil and gas operations, such as the Bakken and Marcellus Shale plays (in the Williston and Appalachian Basins, respectively), appear to have a paucity of induced seismic events (e.g., Ellsworth et al., 2015). Frohlich et al. (2015) specifically investigated the seismicity in the Williston Basin during the Transportable Array (TA) seismograph network deployment in 2008–2011. Despite increases of nearly 400% in annual injected volumes in the Williston Basin since 2009, very low levels of seismicity were observed; nine regional earthquakes were identified, but only one was suggested to have possibly been induced (Frohlich et al., 2015). Similarly, a recent study in Pennsylvania determined there was a lack of seismicity associated with either HF or WD (Hommay, 2015). This finding might be unexpected considering that the neighboring state of Ohio has had three documented sequences induced by WD and four sequences induced by HF with events M ≥2 (Skoumal et al., 2014, 2015a, 2015b, 2015c, 2016a).

In a wide variety of cases where induced seismicity has been linked to WD, researchers have noted that injection was into either the crystalline basement or the basal layer immediately above (e.g., Healy et al., 1968; Nicholson and Wesson, 1990; Seeber et al., 2004; Horton, 2012; Kim, 2013; Skoumal et al., 2015b), although there have been documented cases at larger distances from the basement (e.g., Rubinstein et al., 2014). Hydro-geomechanical modeling supports the idea that the likelihood of induced seismicity may be controlled...
by the distance between injection and critically stressed faults in the basement (e.g., Zhang et al., 2013). Contrary to this hypothesis, Weingarten et al. (2015) specifically investigated the proximity of injection targets to the basement and concluded that this is not such an important factor. Instead, injection rate (particularly for wells injection >300,000 bbl/mo) was found to be the most important well operation parameter affecting the occurrence of induced seismicity.

In this study, we address the question of whether the distance between the injection and the basement influences the likelihood of induced seismicity in the CEUS by investigating the injection activities and seismicity in the Appalachian, Illinois, and Williston Basins (Fig. 1). By using seismic waveform template matching to increase the number of identified earthquakes and then evaluating the seismicity for swarm-like behavior in proximity to WD or HF completions, we aim to better characterize the relationships between industry activities and induced seismic events. Collectively, the results of our investigation suggest that proximity to basement has an important influence on the likelihood of induced seismicity associated with WD and HF in the CEUS. This may have implications for assessment of induced seismic risk related to the siting of new disposal wells and/or the production of hydrocarbons from near-basement reservoirs.

METHODS

To aid in detecting induced seismicity, an optimized waveform template matching procedure was created that can perform tens of millions of template correlations every second to rapidly characterize the temporal patterns of repetitive seismic sequences (Skoumal et al., 2014). Matches are defined as cases where the network normalized correlation coefficient (NNCC) exceeds the daily median absolute deviation (MAD) multiplied by a coefficient of 15, a demonstrated conservative detection threshold for regional template matching (e.g., Skoumal et al., 2014). Correlating a randomly generated template against a random year-long signal at 40 samples/s would result in about one false positive based on what 15 × MAD represents, theoretically. We reviewed all matched waveforms to ensure there were no spurious detections.

Skoumal et al. (2015c) applied multi-station waveform template matching to all earthquakes cataloged in Ohio since the arrival of nearby EarthScope TA stations. They found that all earthquakes within 5 km of either WD or HF operations had a swarm-like nature and occurred in areas with no previously documented seismicity. The remaining earthquakes, all of which were >10 km from a WD or HF well, were found to lack a swarm-like nature and all occurred in areas with previously documented seismicity. They identified the three previously documented induced sequences of Youngstown (e.g., Kim, 2013), Poland Township (Skoumal et al., 2015a), and Harrison County (e.g., Friberg et al., 2014). The approach also suggested two additional cases of induced seismicity in Belmont-Guernsey and Washington Counties (Skoumal et al., 2015c). In addition to spatiotemporal correlations between earthquakes and a suspected anthropogenic source, these studies also suggest that unusual swarm-like behaviors in regions that lack previously documented seismicity can be used to identify induced seismicity.
We expand upon previous regional template matching work done in Ohio by Skoumal et al. (2015c) to include Pennsylvania and West Virginia using stations N54A, M54A, and O56A (Fig. 1). We constructed templates from nine cataloged events in Pennsylvania and 14 events in West Virginia since recording at those stations began in 2010. We also applied the technique to the Williston Basin using stations MDND, DGMT, and LAO. We constructed 25 templates for eastern Montana, 16 for western North Dakota using 16 earthquakes since 2008 in the National Earthquake Information Center (NEIC) catalog (http://earthquake.usgs.gov/data), and an extra nine events identified by Frohlich et al. (2015). In the Illinois Basin, we used stations WCI, BLO, and OLIL to construct templates from 21 earthquakes in the southern Illinois and Indiana area since 2008 in the NEIC catalog. We use catalog hypocenters when plotting these earthquakes in maps and cross-sections except in a few previous Appalachian Basin cases where detailed studies are available.

Following the approach described by Skoumal et al. (2016a), we approximated magnitudes of the matched earthquakes through a simplified Richter scale approach:

$$M_L = \log_{10} \left[ \frac{A}{A_0} \right].$$  

For each station and component, we calculated a scale factor ($A_0$) using the peak-to-peak filtered S waveform amplitude ($A$) for all existing cataloged events, and took the median of the $A_0$ from all of these cases as a uniform $A_0$ for the estimation of magnitudes for matched events. For each matched event, we calculated a magnitude at each station and component, and took the median value as our final magnitude. These magnitudes are likely not as accurate as moment magnitude calculations, but provide a uniform means to estimate relative magnitudes for large numbers of small events, which is sufficient for our study.

To quantify swarm-like behavior, we compared the number of events above a magnitude threshold to the maximum magnitude in the sequence (Fig. 2). This magnitude threshold was set at M 1, a threshold larger than the $M_L$ expected from prior work achieved using similar epicentral distances and station quality (e.g., Skoumal et al., 2015c). Vidale and Shearer (2006) pioneered this type of plot for distinguishing between the frequency-magnitude patterns of swarms and mainshock-aftershock sequences. Holtkamp and Brudzinski (2011) proposed a boundary between swarms and mainshock-aftershock sequences based on their analysis of subduction zone swarms and the work of Vidale and Shearer (2006) for Southern California seismicity. Skoumal et al. (2015c) proposed that the boundary could be extended to the small magnitudes we are considering in this study based on patterns in induced seismicity. Following that study, we use the same boundary in Figure 2 as a key indicator of whether sequences are induced swarms or natural mainshock-aftershock sequences. In order to evaluate the relationships between observed seismicity and depth from the WD or HF formation to the crystalline basement, we collected recent sedimentary cover thickness and basement depth maps for the Appalachian Basin (Ohio, Pennsylvania, and West Virginia) (Baranoski, 2013; Alexander et al., 2005; Patchen et al., 2006), Illinois Basin (Illinois, Indiana, and Kentucky) (ISGS, 2015), and Williston Basin (North Dakota and Montana) (Anderson, 2009; Bergantino and Clark, 1985). We chose these areas in part because of the available basement depth determinations. We digitized available basement depth maps and combined those from the same basin using a minimum curvature surface fitting routine (Smith and Wessel, 1990). Resulting basement depth surfaces are available in the Supplemental Material1. We compared the basement depth surfaces with cataloged seismic events and well locations obtained from databases compiled by state oil and gas regulators. Injection-well volumes from WD wells were obtained from state geological survey and oil and gas regulatory agencies in Indiana, North Dakota, Montana, Ohio, and Pennsylvania. Volumes from Kentucky, Illinois, and West Virginia were not available at the time of writing. HF well locations and completion depths were compiled from the FracFocus chemical disclosure registry (https://fracfocus.org/) and state agencies, when available.

**RESULTS**

Presence or Lack of a Swarm-Like Nature

**Appalachian Basin**

Template matching of all 51 cataloged earthquakes in Ohio between 2010 and 2015 reveals five swarm-like sequences that contain 50–500+ $M > 1$ events (Fig. 2A), all of which were found to have been induced (Skoumal et al., 2015c). When the same approach is applied to the 57 recorded earthquakes in other neighboring states of the Appalachia study region, we found three additional sequences that demonstrated swarm-like behavior with strong spatiotemporal correlations to injection activities (Fig. 2B).

When the nine earthquakes cataloged in Pennsylvania between 2010 and 2016 were used with template matching, only one cataloged earthquake was found to have occurred as a swarm of smaller-magnitude events while the others were individual events. This swarm occurred during April 2016 in North Beaver Township (Fig. 2B), located near the Pennsylvania—Ohio border and associated with hydraulic fracturing in the Utica Shale and Point Pleasant Formation (see Supplemental Material [footnote 1]). Despite over 8000 HF wells in Pennsylvania targeting the shallower Marcellus Shale between 2010 and 2016, no earthquake swarms have yet been associated with these operations.

Template matching applied to 24 earthquakes cataloged in West Virginia between 2010 and 2015 revealed two sequences in Braxton and Gilmer Counties that demonstrated swarm-like behavior (Fig. 2B) and were also both found to be spatiotemporally linked to WD and HF, respectively (see Supplemental Material [footnote 1]). Beginning in 2009, WD in Braxton County induced
earthquakes up to M 3.4. The West Virginia Department of Environmental Protection (WVDEP) ordered reduced injection rates at this well following the M 3.4 event, and further restricted both the volume and the rate after an additional M 2.8 earthquake occurred in January 2012. The well was eventually shut in after a M 3.0 in 2013. Adjacent to Braxton County, we found that HF targeting the Marcellus Shale induced earthquakes during July–August 2013 in Gilmer County. We detected 52 earthquakes in the swarm, including three M~2.7 events that were located within ~3 km of the HF operation. See the Supplemental Material [footnote 1] for further description of these sequences.

Template matching applied to 24 earthquakes cataloged 2010–2015 in eastern Kentucky and western Virginia revealed no swarm-like behavior (Fig. 2B) and are best explained as naturally occurring seismicity.

**Illinois Basin**

For the southern Illinois and Indiana portion of the Illinois Basin, Weingarten et al. (2015) indicated that seismicity was associated with a swath of WD
wells. To our knowledge, the only previously suggested induced sequences in the Illinois Basin are the 1995–1996 Wabash Valley M <1.8 sequence associated with secondary oil recovery (Pavlis et al., 2002; Eagar et al., 2006) and the 2013–present Decatur M <1.26 sequence associated with carbon sequestration (Kaven et al., 2015). Both the Wabash Valley and Decatur sequences were not included in the earthquake catalog used by Weingarten et al. (2015). The association of earthquakes in southern Illinois with injection activities by Weingarten et al. (2015) is further questioned by historical seismicity predating the wells that formed the Wabash Valley seismic zone, which suggests that the seismicity observed in geographic proximity to wells would be expected to have occurred naturally (e.g., Stauder and Nuttli, 1970; Hamburger and Rupp, 1988; Munson et al., 1997).

Template matching of 26 recorded earthquakes since 2008 in the Illinois Basin did not identify any evidence of seismic swarms (Fig. 2D), suggesting that these cataloged earthquakes were more likely natural in origin. It should be noted, however, that our present study is limited by the reliance on a catalog of earthquakes of M >2.0 identified by regional seismic networks from which the template matching we employ is based. As such, relatively low-magnitude induced events, such as those associated with the carbon sequestration in Decatur, are unlikely to be identified given the methodology employed in our study.

**Williston Basin**

We also applied our template matching to follow up on a recent investigation of seismicity in the Bakken Shale play in the Williston Basin of North Dakota and Montana. Previous work in the region by Frohlich et al. (2015) identified only three earthquakes occurring near WD wells, with only one with the possibility of being induced. Our investigation found that all 16 recorded earthquakes in the Bakken production region since 2008 have no more than two similar events, suggesting a lack of a swarm-like nature and supporting a natural origin (Fig. 2C). This includes the three earthquakes recorded near Williston Basin WD wells and the one described to be potentially induced by Frohlich et al. (2015).

**Proximity to Crystalline Basement**

For the Appalachian Basin, we constructed a unified basement depth surface across Ohio, West Virginia, and Pennsylvania (Fig. S1 [footnote 1]) utilizing recent determinations by Baranoski (2013), Alexander et al. (2005), and Patchen et al. (2006). We find that there are significant differences (~7 km) between the depth to crystalline basement using more recent data than those used in the Mooney and Kaban (2010) compilation in parts of our study area, while mean absolute differences are on the order of ~0.5 km (Fig. S2 [footnote 1]). We also determined the depth of both wastewater injection and unconventional hydrocarbon reservoirs (Ordovician Point Pleasant Formation–Utica Shale and the Devonian Marcellus Shale) utilizing available digital records (Cardwell et al., 2010; Patchen et al., 2006; PGs, 2015; ODNR, 2015) as well as the thicknesses of the Salina Group evaporites that underlie the Marcellus Shale (Ryder et al., 2009, 2012). This was combined with our basement depth surface to create a more accurate estimate of the proximity between operations and the basement (Fig. 3). We determined that all but one WD and HF wells associated with known induced seismic events were within ~700 m of the crystalline basement. The one exception was in Washington County, Ohio, where the injection interval is ~1.5 km above basement (Fig. 4).

In Pennsylvania, only one well was within 1 km of the basement. This is a result of regionally eastward-deepening basement (due to overall stratigraphic thickening of Paleozoic strata and the presence of the Rome Trough), shallower (<2 km depth) injection wells, and horizontal production wells almost exclusively targeting the Marcellus Shale rather than the deeper Utica–Point Pleasant formations. In West Virginia, similar factors result in no wells within 1 km of the basement. The two suspected WD and HF induced earthquake sequences in Braxton and Gilmer Counties occurred within the sedimentary section at ~3.7 km and ~4.2 km above the basement, respectively (Fig. 4C; Fig. S5 [footnote 1]). While a majority of induced earthquakes in the United States have occurred within the Precambrian basement, these sequences highlight the potential to induce earthquakes in the sedimentary section given the presence of nearby, critically stressed faults.

A recently created basement depth map (ISGS, 2015) across Missouri, Illinois, Indiana, and Kentucky was used for the Illinois Basin area (Fig. 5) and was found to be similar to the Mooney and Kaban (2010) compilation (Fig. 6). A structure contour map of the New Albany Shale and FracFocus reports were used to estimate hydraulic fracturing depths and locations, and the disposal well locations and depths were retrieved from state databases (ISGS, 2015, 2016; KGS, 2014; MGS, 2016). Located in central Illinois, the 2.1-km-depth Decatur CO2 sequestration site is the deepest injection well in the Illinois Basin. The large-volume (~1000 t/d) sequestration site targeting the 460-m-thick Mount Simon Sandstone directly overlies the rhyolite basement and has been associated with Mw ≤1.26 microseismic activity (Kaven et al., 2015). Proceeding southward through Illinois, the Illinois Basin thickens, with the basement reaching depths >3 km. Both the shallow WD wells and the handful of horizontal wells targeting the New Albany Shale are >1 km from the Precambrian basement.

For the Williston Basin, the basement depth model of North Dakota from Anderson (2009) was used to determine interval distances (Fig. 7) and was found to be similar to the Mooney and Kaban (2010) compilation (Fig. 8). Well reports from a state database were used to determine disposal well locations (NDICOGD, 2011). A structure contour map of the base of the Three Forks Shale in conjunction with well reports from the state database were used to estimate hydraulic fracturing locations (EIA, 2016; NDICOGD, 2011).

In western North Dakota, the location of the thickest sedimentary section of the Williston Basin, the Bakken and underlying Three Forks formations are ~1.5–2 km above the Precambrian basement. The basin gradually thins into Montana where the hydraulic fracturing operations targeting the
Bakken–Three Forks reach ~1 km above the basement. Most brine disposal wells in the Williston Basin are at relatively shallow depths (>2.5 km above the Precambrian basement) in the Cretaceous Dakota Formation.

**Lithologic Characteristics beneath the Target Interval**

The lithologic characteristics of sedimentary strata situated between target intervals and the crystalline basement were also investigated to evaluate the role they may play in diminishing the transmission of fluid pressures or poroelastic stresses during fluid injection.

The Marcellus Shale in the Appalachian Basin is underlain by ~300–400 m of halite, anhydrite, and shale of the Silurian Salina Group (Ryder et al., 1992, 2012) (Fig. 4). The presence of these lithologies could provide an effective sealing mechanism for existing faults and fractures so as to prohibit effective communication of elevated pore-fluid pressures to critically stressed, optimally oriented basement faults (Fisher and Knipe, 2001; Warren, 2007; Pluymakers et al., 2014). In addition, evaporites may inhibit poroelastic stress transmission between hydraulically fractured lithologies and basement fault zones. In either case, the presence of Salina Group evaporites beneath the Marcellus Shale may provide an alternative explanation to the basement proximity hypothesis as to why areas in Pennsylvania and West Virginia that have experienced extensive Marcellus development have little evidence supporting the occurrence of induced earthquakes. The presence of thin anhydrite beds (<15 m thick) in Mississippian and Ordovician strata in the Illinois Basin (Smith et al., 1973; Johnson et al., 1989) may play a similar role, as these intervals are beneath most of the WD and HF wells in the basin, respectively.

Sealing lithologies do not fully explain our observations, however. For example, while parts of the Williston Basin contain Middle Devonian evaporites >100 m thick (Fig. 8) (LeFever and LeFever, 2005), the lack of significant evaporites in Montana or southern North Dakota cannot fully explain the paucity of induced seismic events. Additionally, in the Appalachian Basin, the locations...
Figure 4. Simplified geological cross-sections in the Appalachian Basin (see Fig. 3 for location), showing the Marcellus Shale (green), Salina Group evaporites (Ryder et al., 2009, 2012) (orange), Point Pleasant Formation–Utica Shale (red), Precambrian basement (dark gray shading), and strata above the basement (light gray shading). Depth values are relative to sea level. Small circles are depths and locations of hydraulic fracture stimulations, and blue lines are wastewater disposal wells. Stars are induced earthquake sequences: T—Trumbull County, Ohio (OH); Y—Youngstown, OH; P—Poland Township, OH; N—North Beaver Township, Pennsylvania (PA); H—Harrison County, OH; B—Braxton County, West Virginia (WV); G—Gilmer County, WV; W—Washington County, OH (Skoumal et al., 2015c; Supplemental Material [footnote 1]). Dashed line is basement depth from Mooney and Kaban (2010) that was used by Weingarten et al. (2015) (See Figs. S1 and S2 [footnote 1]).
of the probable WD and HF induced sequences and their associated wells in Braxton and Gilmer Counties, West Virginia, are underlain by ~300 m of Silurian Salina Group and Ordovician anhydrite and anhydritic dolostone (Ryder et al., 1992).

**Injected Volumes**

Several studies have pointed to injection rates being the primary factor in determining the degree to which induced seismicity occurs (NAS, 2013; Weingarten et al., 2015). However, when we compile the monthly injected volumes for WD wells in each of our three study regions, we find that the injected volumes are substantially higher for the Williston Basin on average, despite no clear cases of induced seismicity (Fig. 9). With injection rates in excess of 350,000 bbl/mo, the largest WD volumes in our study regions were located in the Williston Basin. There were >150 wells with monthly injection volumes >75,000 bbl/mo in the Williston Basin, while no WD wells in the Appalachian or Illinois Basins exceeded this rate. However, the induced seismicity related to WD wells in Ohio were associated with the three largest volumes in the Appalachian Basin. Likewise, the Decatur carbon sequestration site has much larger volumes than the WD wells in the Illinois Basin that have no detected seismicity.

**DISCUSSION**

**Proximity to Stressed Faults**

It should be noted that proximity of WD and HF stratigraphic targets to basement is not in itself a controlling factor in the occurrence of induced seismic events. More accurately, induced events are likely a consequence of the proximity of wells to critically stressed and optimally oriented faults existing in basement lithologies that have a propensity to generate recordable seismicity during reactivation (e.g., Zhang et al., 2013). Additionally, the overall porosity...
Figure 6. Simplified geological cross-sections in the Illinois Basin (see Fig. 5 for location), showing the New Albany Shale (green), Precambrian basement (dark gray shading), and strata above the basement (light gray shading) (ISGS, 2015). Depth values are relative to sea level. Small circles are depths and locations of hydraulic fracture stimulations, and blue lines are wastewater disposal wells (ISGS, 2016; IGS, 2016; 2016 FracFocus report). Purple line is the Decatur carbon sequestration well, and the star indicates seismicity associated with it (Kaven et al., 2015). Earthquakes are from the National Earthquake Information Center (NEIC) catalog (http://earthquake.usgs.gov/data) and occurred over the past 10 yr (diamonds) and the 20 yr before that (crosses). Note that depths of shallow events are typically fixed at 5 km due to lack of nearby stations. Symbols plotted below the cross-sections are earthquakes within the cross-section borders that occurred at deeper depths. Dashed line is basement depth from Mooney and Kaban (2010) that was used by Weingarten et al. (2015). IL—Illinois; IN—Indiana.
and permeability of targeted saline and hydrocarbon formations relative to injected volumes, rates, and pressures associated with WD and HF operations are also likely to be important factors. This is particularly the case in regions such as the Appalachian Basin where burial-related diagenetic effects may severely reduce the permeability of basement-proximal strata in deeper parts of the basin (Battelle Memorial Institute, 2015) such that injected fluids are in part dispersed through fracture networks associated with existing faults. Conversely, permeability enhancement associated with fault-related fluid flow may aid pore fluid pressure diffusivity during injection (Schultz et al., 2016).

We find that when operations were located near the basement, the chances of induced seismicity are greatly increased (Fig. 10). When fluids were injected directly into the basement or the overlying basal sedimentary strata, ~10% of the wells (three of 30 wells) were associated with induced sequences that contained at least one M >1 earthquake. The chances a well was associated with earthquakes at moderate distances (500–1000 m) from the basement dropped to ~2%–3% (58 of 2433 wells), while <<1% of the operations at greater distances induced events.

To assess our uncertainties in making these interpretations, we performed bootstrap resampling of the well and earthquake data sets (Figs. 10A and 10B) 1000 times, randomly removing 10% of the wells and recalculating the percentage of wells associated with induced seismicity at each well-to-basement distance bin (Fig. 10C). As this primary approach can only provide insight into depth bins that have identified induced earthquakes, we also determine the occurrence percentage of wells associated with induced seismicity in each well-to-basement distance bin without any prior induced seismicity by calculating the percentage as if an additional, hypothetic well would induce earthquakes. In other words, this represents the percentage of wells with induced earthquakes if the next well drilled at that distance from the basement generated seismicity. While this secondary approach has minimal impact on the uncertainty for bins with many wells, it provides a useful upper estimate of uncertainty for well-to-basement distance bins lacking earthquakes.

A greater likelihood of slip occurs if a fault is optimally oriented for slip in the contemporaneous state of crustal stress and located in the Precambrian basement. Nearly all such faults remain unmapped until imaged by well-located hypocenters, including the faults in Ohio (e.g., Skoumal et al., 2015c), Illinois (Pavlis et al., 2002; Kaven et al., 2015), Pennsylvania (see Supplementary Material [footnote 1]), and West Virginia (see Supplemental Material [footnote 1]).

Geologic Influences on Induced Seismicity

While we suggest that injection within 1 km of the basement has the greatest risk of inducing earthquakes, this result may differ depending on the geologic structures, strata, and stress states present in the region. For example, the WD and HF wells that induced seismicity in Braxton and Gilmer Counties...
in West Virginia are on the southeastern margin of the Rome Trough, ~4 km above the basement. Geologic evaluation of the Braxton County WD-associated sequence indicates that wells were injecting into fractured Devonian shale and siltstone near a basement-involved fault zone situated at the eastern margin of the Rome Trough (McDowell et al., 2014). Attempts at establishing a link between preexisting basement faults and the possible HF-related sequence in Gilmer County have not been conclusive, but such a relationship might be a reasonable explanation considering the location of Gilmer County in the Rome Trough boundary region (Ryder et al., 1992). Similarly, earthquakes associated with the Washington County, Ohio, seismic sequence occurred both in the upper parts of the crystalline basement and within lower Paleozoic sedimentary rocks. Although the WD well associated with these events is injecting into Silurian strata ~1.75 km above the basement, the well is also situated near faults that cut both the injection interval and underlying Proterozoic basement (Free et al., 2015). Given such relationships, existing moratoriums on injection near known faults, such as those implemented in Arkansas and Ohio, may be effective at reducing, but by no means eliminating, the likelihood of induced seismicity.

Figure 8. Simplified geological cross-sections in the Williston Basin (see Fig. 7 for location), showing the Bakken and Three Forks formations (green), Precambrian basement (dark gray shading), and strata above the basement (light gray shading) (EIA, 2016; Anderson, 2009). Depth values are relative to sea level. Small circles are depths and locations of hydraulic fracture stimulations, and blue lines are wastewater disposal wells (NDICOGD, 2011). Earthquakes (identified from the National Earthquake Information Center catalog [http://earthquake.usgs.gov/data] and Frohlich et al. [2015]) used for template matching are shown as squares. Note that earthquake depths are fixed at 5 km, as the Transportable Array station spacing of 70 km does not allow reliable depth determination. Orange line represents the Middle Devonian evaporite thickness (LeFever and LeFever, 2005). Dashed line is basement depth from Mooney and Kaban (2010) that was used by Weingarten et al. (2015). MT—Montana; ND—North Dakota.
Influence of Injection Rate

Our results stand in contrast to those of Weingarten et al. (2015), who found that injection rate (particularly >300,000 bbl/mo) was a more important well operation parameter affecting the occurrence of induced seismicity than proximity of well operations to basement. However, Weingarten et al. (2015) noted that a potential limitation with their approach was that the basement depths were based on sediment thicknesses gridding compiled by Mooney and Kaban (2010), primarily derived from Frezon et al. (1983). Based on a handful of direct comparisons between the Mooney and Kaban (2010) model and observed basement depths, Weingarten et al. (2015) concluded that depth uncertainties are of the order of ±15%. Our analysis suggesting a mean absolute difference of ~0.5 km (Fig. S2 [footnote 1]) between the model of Mooney and Kaban (2010) and those of other basement studies is comparable with the reported uncertainties, but wells in proximity to induced sequences were also found to have multiple-kilometer errors. When taking into account the error in basement depth over the CEUS, Weingarten et al. (2015) did not observe a significant correlation between wells injecting near basement and earthquakes using a bootstrap resampling method. We believe that focusing on areas with improved basement depth estimates, particularly in the Appalachian Basin, was a key reason we were able to discern a relationship between proximity to basement and likelihood of induced seismicity.

Although our study finds that high injection rates alone are not sufficient to produce induced seismicity, this does not preclude injection rate from being a
necessary condition. No wells associated with induced seismicity in our study regions had injection rates >300,000 bbl/mo, a limit above which Weingarten et al. (2015) found injection rate to be much more likely to be associated with induced earthquakes. When we consider data from Oklahoma, we note that regional-scale small-volume injection occurred for decades into the Arbuckle Group, which is now known to be hydraulically connected to the basement (Walsh and Zoback, 2015). These wells operated during time periods with relatively minor amounts of seismicity, with the rapid seismicity rate increases not occurring until large-scale, high-rate injection began in 2008 (Keranen et al., 2014; Walsh and Zoback, 2015). When regulators mandated that operators plug back all wells from crystalline basement injection zones, it had no discernable effect on seismicity rates, likely due to the hydraulic connection between the injection reservoir and basement faults (Langenbruch and Zoback, 2016). However, subsequent mitigation efforts to reduce certain regional and individual well injection rates appears to have been successful (Langenbruch and Zoback, 2016). These observations suggest that injection rate is a factor contributing to the occurrence of induced seismicity, but our study suggests that other factors, such as proximity to faults, are important as well.

Limitations and Future Work

Although we have attempted to improve detection thresholds using template matching, the approach used in our study relies on cataloged earthquakes. As suggested by Skoumal et al. (2016a), there may be induced seismic sequences in the CEUS with maximum magnitudes below traditional earthquake detection levels. If this is the case, the sequence would remain undetected. Efficient, autocorrelation-like approaches, such as the Fingerprint and Similarity Thresholding (Yoon et al., 2015) or Repeating Signal Detector (Skoumal et al., 2016a) algorithms, are more capable of detecting small, repeating seismic events than traditional detection methods. These new approaches could be applied to the CEUS to confirm the absence of swarm-like seismicity in the southern Illinois Basin, the eastern Appalachian Basin, and the Williston Basin. Future work might consider the distance between the target interval and the basement in other basins, especially in states like Oklahoma and Texas where numerous induced sequences have been identified (e.g., Walsh and Zoback, 2015; Frohlich et al., 2015). Oklahoma in particular has experienced much higher seismicity rates than other areas of the CEUS, which have been largely attributed to WD (e.g., Walsh and Zoback, 2015) with a small percentage associated with HF (e.g., Holland, 2013; Skoumal et al., 2016b). Our finding that fluid injection near the basement raises the likelihood of seismicity may also apply to Oklahoma, as many of the disposal wells inject into the lower Paleozoic Arbuckle Group (e.g., Keranen et al., 2014). However, a more detailed study would need to be done to determine the distance of the injection intervals above the basement in this region in this region. In the Fort Worth Basin in Texas, both basement-proximal WD and basal proximal HF in the Barnett Shale are associated with earthquake swarms that suggest that the events were induced (Frohlich, 2012; Smith et al., 2016). More detailed studies of basement-proximal WD and HF horizons are required in both Texas and Oklahoma to confirm these possible relationships.

CONCLUSIONS

Based on (1) unified modified basement maps compiled from recent studies, (2) well logs, and (3) swarm-like seismicity patterns determined by regional template matching, we suggest that wastewater disposal and hydraulic fracturing in proximity to the basement increases the likelihood of inducing seismic events in the Appalachian, Illinois, and Williston Basins. While we find that eastern Ohio, western Pennsylvania, and central West Virginia have recently been host to a handful of induced seismicity sequences, central Pennsylvania, southern Illinois–Indiana, and North Dakota–Montana all demonstrate little evidence for induced seismicity. We perform regional template matching for all cataloged earthquakes to produce more complete sequence catalogs and provide us with a better insight into the swarm-like nature of the sequences. If injection rates were the primary factor controlling the occurrence of induced seismicity as suggested by Weingarten et al. (2015), the Williston Basin, which contained the largest injected volumes of the three basins, should demonstrate evidence of induced seismicity. However, we found no significant evidence for induced seismicity in this area. We suggest that the most important factor to account for induced seismicity (or lack thereof) in the Appalachian, Illinois, and Williston Basins is the proximity of the target formations to the activated faults, most of which were located in Precambrian basement. We therefore suggest that regions that have substantial industry activity near (<1 km above) the Precambrian basement have a greater likelihood of inducing seismicity than more distal wells.

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