Environmental Earth Sciences (2020) 79:271
https://doi.org/10.1007/s12665-020-09008-0

ORIGINAL ARTICLE

Hydraulic fracturing operation for oil and gas production and associated earthquake activities across the USA

Valeria Villa[1,2] · Ramesh P. Singh[1]

Received: 14 February 2019 / Accepted: 22 May 2020

Abstract
Hydraulic fracturing (fracking) operations, associated with horizontal drilling for oil/gas production, are known to induce earthquakes from fluid injection in disposal wells. In recent years, numerous studies have shown a close relationship between induced seismic activities and the high-pressure injection of wastewater, especially in Texas, Kansas, and Oklahoma. Detailed analysis of 17 major fracking locations across the USA has been carried out to study the impact of horizontal wells and the corresponding injected wastewater on earthquake activities. Earthquake data for the period 1998–2018 obtained from the USGS earthquake catalog shows an increase in frequency of earthquakes within a radius of 150 km at fracking locations, prominently in south-central USA. The stimulation of earthquakes depends on the amount of injected water in both horizontal and disposal injected wells, and the geology, hydrological, and geophysical settings nearby the drilling site. The observed seismicity increases with the number of horizontal wells in Texas (correlation $R^2 = 0.726$) and Oklahoma (correlation $R^2 = 0.636$) at the fracking locations.

Keywords Fracking · Hydraulic fracturing · Earthquake · Injection wells · Oil production · Shale formation

Introduction

A surge in earthquakes has been observed near hydraulic fracturing (fracking) operations at US oil and natural gas drilling sites (Boss et al. 2012; Ellsworth 2013; Rubinstein and Mahani 2015; Pei et al. 2018). Induced seismicity has been discussed in the North American plate by many (Flewelling et al. 2013; Pei et al. 2018). In this study, we provide a statistical analysis of observations between earthquake data and drilling sites at 17 major fracking locations across the USA.

Fracking uses horizontal drilling for oil and natural gas exploration in low-permeability shale layers. This method operates the extraction process through deep injection of high-pressure fluid to pressurize the deep-rock formations. The oil and natural gas trapped in deep-rock formation move freely through enhanced fractures and permeability. The drilling starts at a vertical distance up to 1500–3000 m and horizontally up to 1400 m (Peduzzia and Harding 2013). Once the drilling is complete, the fracking fluid is injected deep at high pressure, strong enough to form fractures, fissures, and cracks in the rock formation that enhance permeability and facilitates the flow of the oil and natural gas (Sneegas 2016; Davis and Fisk 2017). The fracturing fluid resurfaces the well and is disposed at high pressure on nearby reinjection wells from the drilling site (Ethridge et al. 2015; Brudzinski and Kozlowska 2019). Thus, the fracking fluid, a mixture of proppant, water, and chemicals, is injected at high pressure during the extraction and disposal process. As a result of this high-pressure reinjection into the drilling and disposal wells, the fracking process influences the stress and strain in nearby faults, enhancing the local seismicity.

It is well known that high-pressure fluid injection displaces rock and enhances permeability in the shale layers. This process induces earthquakes in nearby fracking sites and is related to the amount of injection fluid. Numerous studies have shown an enhancement in seismic activities in the mid-USA associated with disposal wells (Ellsworth 2013; Westwood et al. 2017; Wu et al. 2018; Brudzinski and Kozlowska 2019). Such triggering of earthquakes was

✉ Ramesh P. Singh
rsingh@chapman.edu

1 School of Life and Environmental Sciences, Schmid College of Science and Technology, Chapman University, One University Drive, Orange, CA 92866, USA

2 Present Address: Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, 595 Charles Young Drive East, Los Angeles, CA 90095, USA

Published online: 31 May 2020

considered as the cause of "intraplate" earthquakes. Although the physics of intraplate earthquakes is not well understood, it is believed that such earthquakes are associated with water withdrawal and fluid injection (Singh et al. 1995; Singh and Singh 1996). High-pressure injection allows sudden changes in the effective pressure that enhances permeability in the underground formation that may trigger earthquakes, which may be one of the triggering mechanisms for intraplate earthquakes. For example, an increase in pore pressure and shear stress can lubricate fault zones and reactivate existing faults, thereby triggering earthquakes when the displacement occurs near a fault (Kocharyan et al. 2011; Davies et al 2013; Rubinstein and Mahani 2015; Eaton and Schultz 2018).

The distance from a drilling site to a nearby fault plays an important role in induced seismicity. Geographic locations with pre-existing fractures have a greater possibility of triggering microseismic events (Wilson et al. 2018). There are two types of microseismic events associated with induced seismicity: dry and wet events. Dry seismic events occur by stress not associated with high-pressure water injection, while a wet event is triggered by a high-pressure-associated stress. In the case of a microseismic wet event, the seismic waves travel over the already critically stressed rocks, creating a tensile failure and producing a cluster of microseismic events (Wangen 2017; Westwood et al. 2017).

Geological environment and data used

Here, we discuss the geological environment of hydrofracturing locations in the USA and the relationship to horizontal drilling and injection wells. We have considered 17 fracking locations from the USGS Hydraulic Fracking map (https://eerscmap.usgs.gov/hfapp/). The coordinates for each fracking location are given in Table 1. The earthquake data are taken from the USGS website (https://earthquake.usgs.gov/earthquakes/map/) for the study periods between 1998 and 2018. Figure 1 shows the earthquake activities in the USA from 1998 to 2018. The epicenters of earthquakes are shown with white circles of magnitude greater than 2.5. The size of the white circles shows the size of magnitude of earthquake events. The 17 locations are encircled in black and cover approximately 70,685 km^2 area of fracking well sites. Furthermore, the number of gas and oil wells and productions of shale were obtained from the U.S. Energy Information Administration (https://www.eia.gov) and the Environmental Protection Agency (https://www.epa.gov). It should be noted that the availability of data concerning the number of wells is not exact for study area due to the limitations of the 150 km radius study region. The observations for each location are discussed below.

Results and discussion

Texas

The oil and gas production in Texas increased dramatically as a result of the fracking technology that made the extraction of oil and natural gas accessible and profitable (Ethridge et al. 2015). The major fracking drilling sites in Texas are encircled within a 150 km radius, as shown in Fig. 2 depicting the Permian Basin, Barnett Shale, Haynesville Shale, Eagle Ford Shale, and the Granite Wash Formation. Figure 3a shows a

Table 1 Coordinates used for USGS earthquake Catalog within radius of 150 km (black circles) around 17 fracking locations across the USA in Fig. 1 (white dots show earthquake distributions within a 150 km radius around fracking locations)

Locations	USGS earthquake catalog coordinates
Permian Basin	31°5′′′44.38″ N 102°2′3.47″ W
Barnett Shale	32°″1′6.62″ N′ 98°′′′45.17″ W
Granite Wash Formation	35°1′′′20.42″ N′ 101°3′′′14.55″ W
Eagle Ford Shale	28°2′′′41.71″ N′ 98°3′′′57.93″ W
Haynesville Shale	32°32′34.04″ N 94°59′23.09″ W
Oklahoma (Woodford Shale)	35°3′′′31.49″ N′ 97°4′′′46.30″ W
Kansas Shale	38°2′′′31.47″ N′ 97°5′′′46.72″ W
San Juan Basin	37°″0′9.88″ N′ 107°4′′′25.71″ W
Piceance Basin	39°4′′′39.48″ N′ 108°4′′′54.88″ W
Denver Basin	40°2′′′24.06″ N′ 104°4′′′32.89″ W
Upper Green River Basin	43°1′′′55.02″ N′ 109°2′′′38.69″ W
Bakken Shale	47°″9′3.06″ N′ 103°1′′′24.74″ W
San Joaquin Basin	36°′′′33.74″ N′ 119°1′′′43.39″ W
Michigan Basin	44°3′′′40.06″ N′ 84°4′′′53.17″ W
Kentucky Shale (part of Marcellus Shale)	37°3′′′39.17″ N′ 83°′′′30.47″ W
Pennsylvania Shale (part of Marcellus Shale)	39°5′′′22.45″ N′ 80°2′′′18.08″ W
Allegheny Mountains (part of Marcellus Shale)	41°″6′0.83″ N′ 76°2′′′34.12″ W

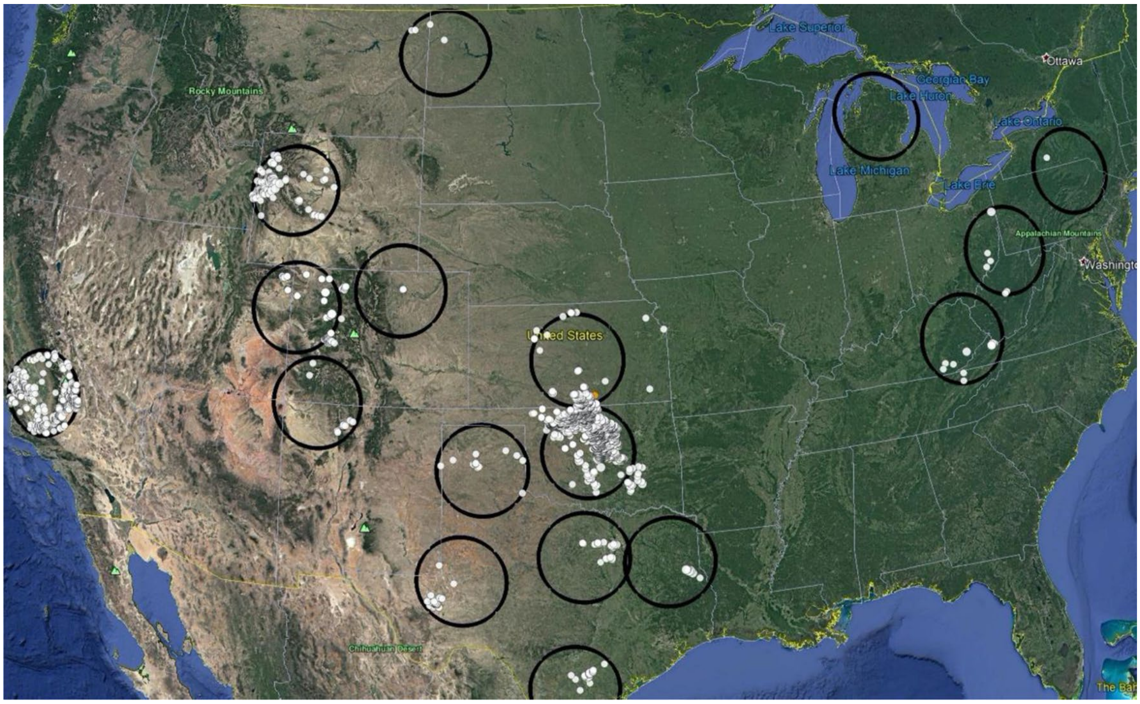

Fig. 1 Location of 17 fracking operations with horizontal drilling in the USA and their respective earthquake activities (epicenters depicted as white dots) from 1998 to 2018 within a 150 km circle radius

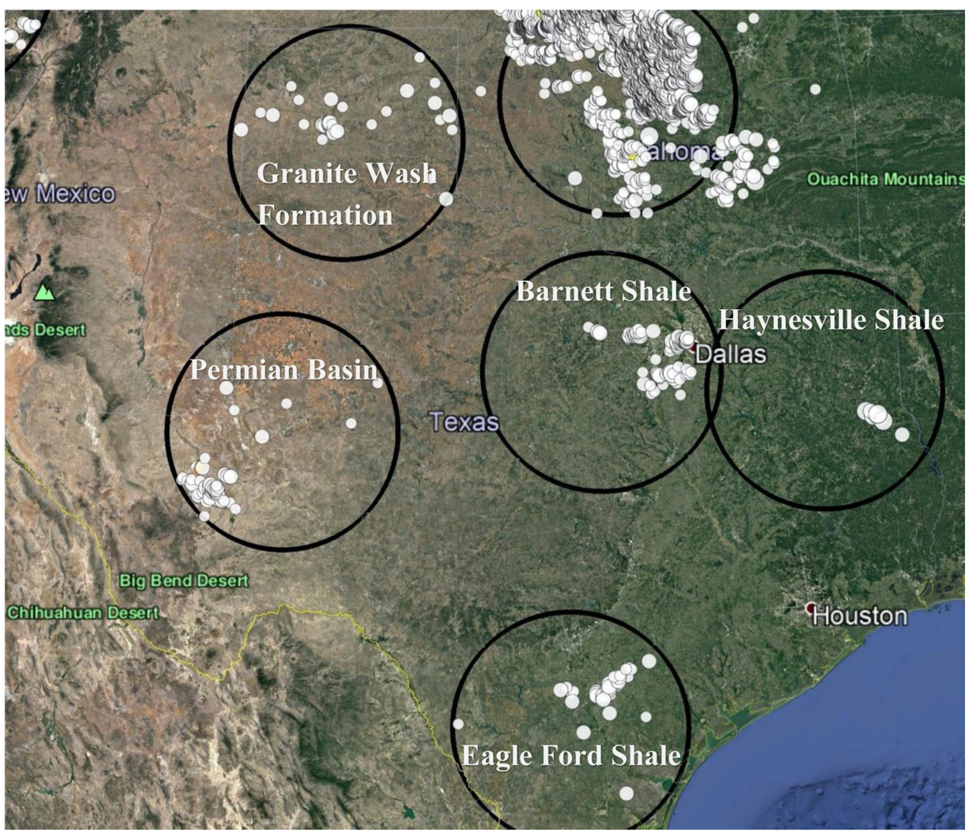

Fig. 2 Map showing five major areas of fracking operations (black circles): the Permian Basin, Granite Wash formation, Barnett Shale, Haynesville Shale, and the Eagle Ford Shale. Distribution of earthquakes with magnitude greater than 2.5 (white dots) from 1998 to 2018 within a 150 km radius

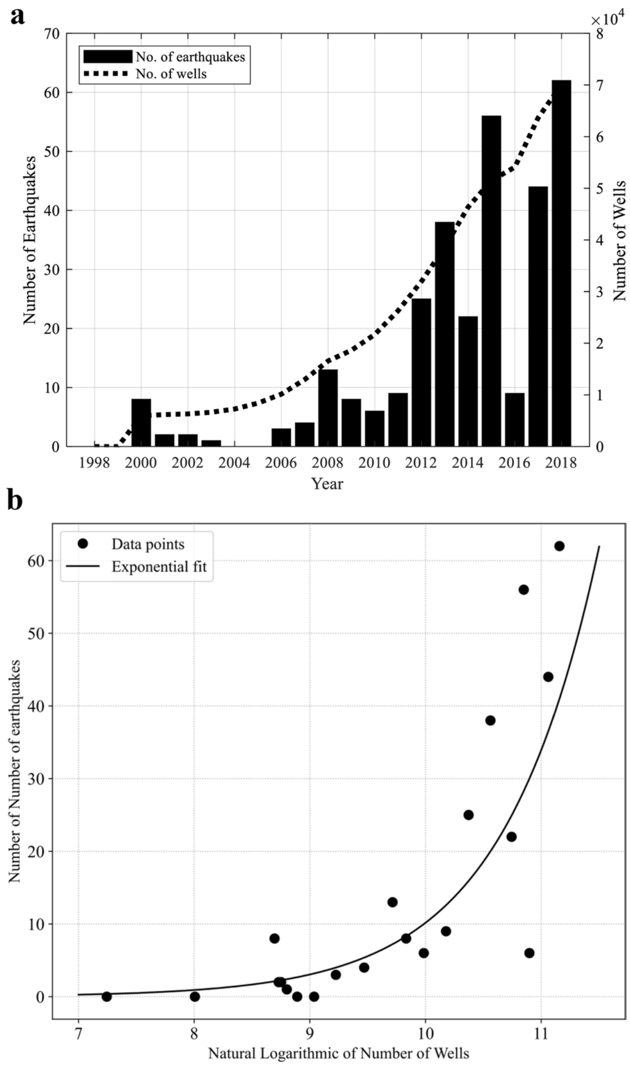

Fig. 3 **a** Total number of earthquake and gas wells for Texas during the study period of 1998–2018, including the Permian Basin, Haynesville Shale, Eagle Ford Shale, Granite Wash Formation, and Barnett Shale. **b** Exponential relationship between the total number of earthquakes and the number of wells in the Texas during the study period 1998–2018 with correlation $R^2 = 0.726$. Earthquake data were taken from the United States Geological Survey (USGS) Earthquake catalog and number of horizontal wells from the Environmental Protection Agency (EPA)

comparison between the total number in the Texas region and the natural gas number of gas wells from the periods 1998–2018. In 1998, the total number of earthquakes in this region was non-existent and the number of gas wells less than 60,000. The total number of earthquakes during the periods 2000–2009 remained in the range of 0 to 13 earthquakes. However, a sharp increase in earthquakes begen in 2012 with a total earthquake count of 27, to 39 in 2013, and 62 in the year 2018. Six years prior to the earthquake surge in 2018, the number of gas wells experienced a spike from 85,000 wells in the year 2010 to a total of 140,000 wells in the years 2012 and 2014. A similar increase in horizontal drilling was found from 5792 to 54,096 wells during the period 2000–2016 (Scotchman 2016). Figure 3b shows an exponential relationship between the number of earthquakes with the increasing number of gas wells from 1998 to 2018.

In 2003, the Barnett Shale was the first location in Texas to have a large number of horizontal wells (Frohlich et al. 2016) due to low permeability of the geological formation and black shale deposits (Shapiro and Dinske 2009; Scotchman 2016) for the fracking process. In this shale formation, we observed an increase in earthquakes in 2012 (Fig. 4). Most earthquake events were of M_W 2.5–3.0. On 7 May 2015, this shale gas reservoir experienced a mild earthquake of M_W 4.0. In this region, more than 23.8×10^6 L of fluid is injected per month (Shapiro and Dinske 2009; Kenomore et al. 2018). An exponential growth of horizontal wells, 17,300 during the period 2000–2013, was linked to the induced seismicity in the Barnett Shale (Ethridge et al 2015). Frohlich et al. (2016) have investigated the earthquakes in the Barnett shale area and found a link with the nearby wastewater disposal wells (Frohlich et al. 2016).

Figure 3b shows the total number of earthquakes and horizontal wells in Texas during 1998–2018. The data show a correlation of $R^2 = 0.726$, with a p value 9.438×10^{-7} between the observed total number of earthquakes and increasing horizontal wells in the Texas region.

The recent developments to fracking allowed extensive drilling in the Eagle Ford Shale beginning in 2009 (Scotchman 2016). Figure 4 shows that this area had 1 earthquake prior to 2008, and afterward a sudden increase to 10 earthquakes during the periods 2008–2012 and 33 earthquakes during 2013–2018. The study region focuses on earthquakes of magnitude greater than 2.5 within a 150 km radius in the Eagle Ford. Frohlich and Brunt (2013) located 62 probable small-magnitude earthquakes, including 58 events not reported in the USGS Earthquake catalog, associated both with extraction and injection in the entire Eagle Ford Shale during 2009 and 2011. The 150 km radius captured a mild M_W 4.8 earthquake on 20 October 2011. Prior to this mild event, 26 earthquakes of around 2.5 magnitude occurred in nearby hydrofracturing well sites. According to Frohlich and Brunt (2013), the M_W 4.8 earthquake event was triggered by the extraction of oil and water due to the depressuring of subsurface fluids. In May 2018, the second mild magnitude earthquake occurred 12 km away from the location of 2011 M_W 4.8 event.

In the Haynesville Shale, horizontal drilling wells increased in 2008 that enhanced earthquakes of $M_W > 2.5$, compared to any other region in Texas (Frohlich and Brunt 2013; Frohlich et al. 2016; Scotchman 2016; Walter et al. 2016). Figure 4 shows that earthquake activity of $M_W > 2.5$ started in the period 2008–2018. There was a total of six earthquakes from 2008 to 2012 and seven from 2013 to 2018. During the period 2012–2014, close to Timpson, TX,

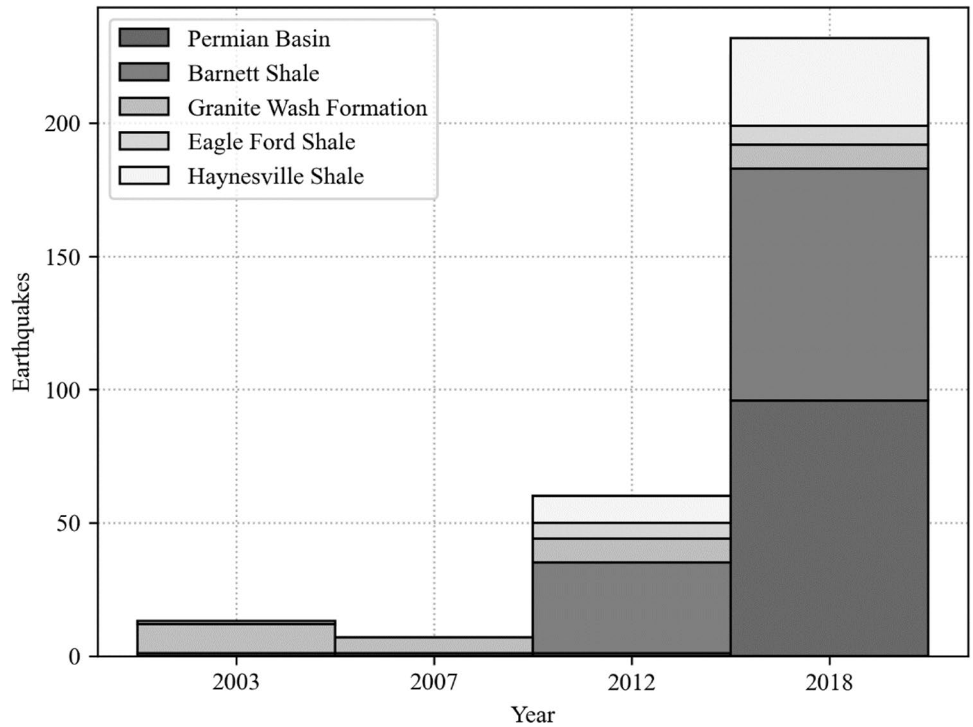

Fig. 4 Frequency of earthquakes in the top five gas producers in Texas during the study period of 1998 to 2018

a cluster of 12 earthquakes occurred. Following an aseismic period, six earthquakes of $M_W > 2.5$ occurred in 2012. This was followed by two lower mid-size earthquakes of M_W 3.9 on 10 May 2012 and M_W 4.8 on 17 May 2012. The earthquake epicenters were close to two wastewater injection wells within 2–3 km distance. A cluster of small earthquake events reflect reactivation of fault zone due to the offset in the ground. This offset may be influenced by enhanced permeability of rock layers (Wilson et al. 2018). Normally, the Haynesville Shale experiences fluid injections of around 16.1×10^6 L per month at the depths of 1.9 km (Kondash et al. 2017). However, the fluid injection increased from 30.2 up to 80.4×10^6 L per month at a depth of 2.5 km beginning in 2009 (Frohlich et al. 2016). The analysis of this region was consistent with earlier induced seismicity studies in the Haynesville Shale area, where it was suggested that recent increase in the earthquakes was plausible due to the volume and depth of wastewater injections (Frohlich et al. 2016; Walter et al. 2016).

The Permian Basin was known as a drilling site before horizontal fracturing started in 2011 (Zemlick et al. 2018). In the year 1970, this basin used conventional sources for oil and gas recovery, particularly in the War-Wink, Kermit-Keystone, and Apollo-Hendrick Fields (Frohlich et al. 2016). During the period 1975–1979, Doser et al. (1992) concluded that seismic events in the basin were probably induced. Frohlich et al. (2016) suggested that the 1966 earthquake was also probably induced, but the trigger was more than one mechanism. After the 1970s, very few small-magnitude earthquakes were observed around this reservoir. Figure 4 shows that earthquakes are prominent in the periods 2013–2018, totaling 96 events. Before 2015, the average seismicity for this region was 2 earthquakes per year, which later increased to 12 in 2015, to 48 in 2018. Due to the history of past seismic and oil exploration activities, the recent surges of earthquakes in Permian Basin, it is difficult to assign a reason for earthquake triggering.

Unlike other regions in Texas, a spike in earthquakes was not observed in the Granite Wash Formation despite containing similar numbers of horizontal wells like the Barnett Shale or the Permian Basin (Fig. 4). This may be due to difference in geological setting. However, further analysis on the deep fault mechanism in this region is needed to make a definite conclusion on the dependence on the geological setting. Such efforts need to consider detailed geological, geophysical, and hydrological information.

Oklahoma and Kansas

Oklahoma is the third largest contributor of natural gas in the USA with a comparable seismicity behavior to California. According to the United States Geological Survey (USGS), two-to-six low-magnitude earthquakes were recorded during the periods 1972–2008; however, the rate of earthquakes increased to 50 events in 2009 and 1047 in the year 2010 (MediaView 2012). Figure 5a shows the total number of earthquakes during the periods 1998–2018. From 1998 to 2008, 17 earthquakes of $M_W > 2.5$ were recorded

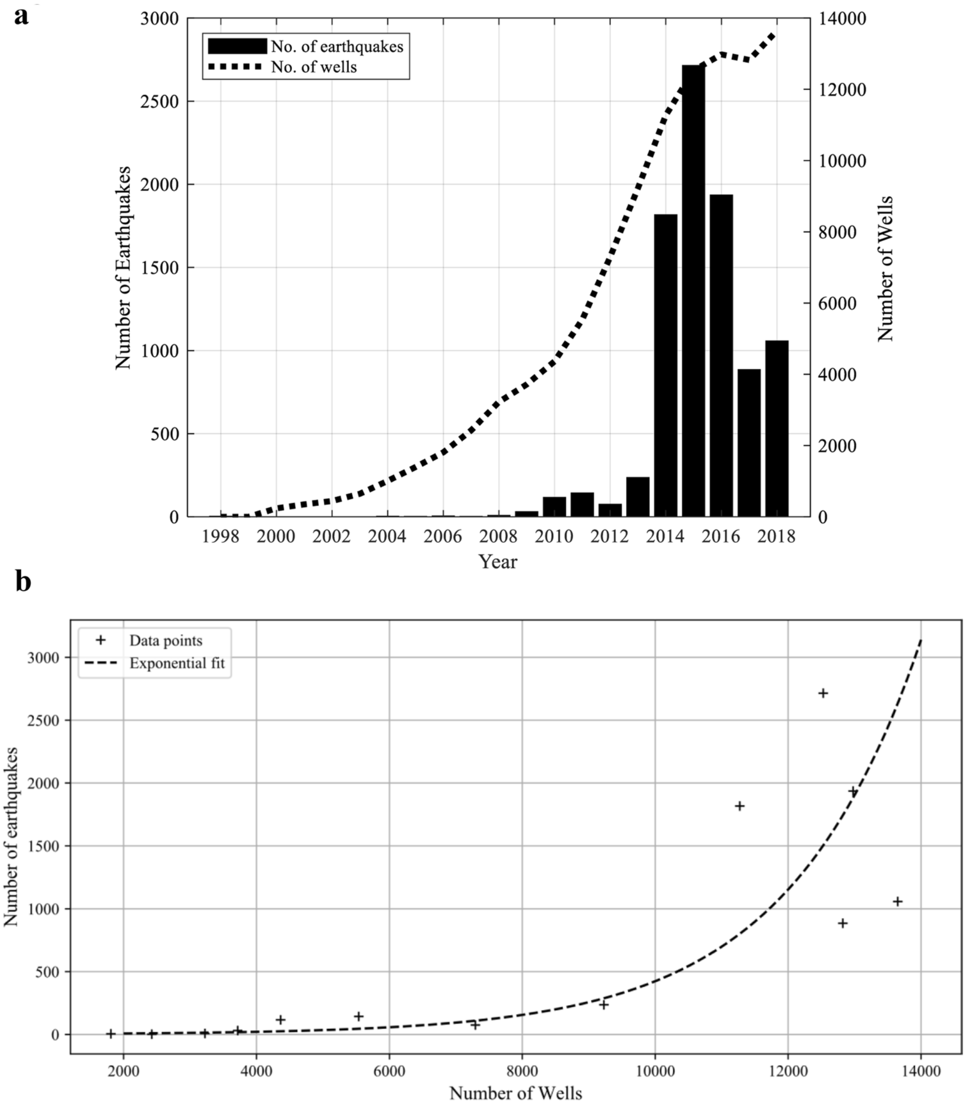

Fig. 5 **a** Total number of earthquakes and horizontal wells in Oklahoma within a circle of 150 km during the study period of 1998–2018. **b** Exponential relationship between the total number of earthquakes and the number of horizontal wells in the Oklahoma region during 2008 to 2018 with $R^2=0.636$

and during the periods 2009–2018, the total number of earthquakes of $M_W > 3.0$ increased up to 8251. One of the largest recorded earthquakes was a magnitude of 5.6 in the year 2016. Prior to 2009, the state was aseismic due to its tectonic setting, and the recent surge in earthquakes is not likely to be tectonic. Studies carried out in this region found that the seismic events were associated with injection wells. Chen et al. (2017) concluded that wells with high amounts of wastewater injection and within a proximity of faults put a greater stress and pressure rate on ancient fault zones in Oklahoma. The reactivated fault (Chen et al. 2017) was from the first deepest hydraulic fracturing operation in Gavin County that caused a cluster of 50 earthquakes of small magnitude (1–2.8) within 3.5 km depth (Peduzzia and Harding 2013).

We have also carried out correlation between seismicity and increasing number of horizontal wells during the periods 2008–2018 in Oklahoma and observed an exponential increase in the number of earthquakes and increasing number of horizontal wells (Fig. 5b). We observe that the number of earthquakes enhanced significantly when the number of wells increased to more than 10,000. The correlation between the observed seismicity and increase in the number of horizontal wells in Oklahoma was found to be $R^2=0.636$.

Prior to horizontal drilling, one or two earthquakes ($M_W < 3.0$) occurred every year in Kansas (Peterie et al. 2018). During 2013–2014, Kansas experienced 137 non-micro magnitude earthquakes and the number of earthquakes increased to 368 in 2016. Analysis shows that the start date in the surge of earthquakes was similar to that of Oklahoma. Earlier studies have suggested that the earthquakes in Kansas can be influenced by disposal wells in Oklahoma that are changing the pore pressure (Hearn et al. 2018; Peterie et al. 2018; Wilson et al. 2018). Hearn et al. (2018) concluded that the triggering of earthquake activities in Kansas was associated with the wastewater injection in the Arbuckle Formation.

San Joaquin Basin, California

California is the third biggest producer of oil and gas in the USA. Its primary focus is on extracting oil, rather than natural gas. The major drilling locations in California include the Geysers, Salton Sea, San Joaquin region, and Coso. About 95% of all fracking operations in California were in the San Joaquin region producing over one-fifth of oil production. Thus, for emphasis on horizontal drilling, the area of study remains in the San Joaquin Valley (Fig. 6). The location selection was supported by a hydraulic fracturing map provided by the USGS (https://eerscmap.usgs.gov/hfapp/) and a study carried out by Long et al. (2015) from the California Council on Science and Technology at Lawrence Berkeley National Laboratory.

The San Joaquin Valley stretches from the north San Joaquin County to south Kern County. The most heavily drilled areas in the Kern County have more than 84,000 oil and gas wells mostly associated with oil production. Figure 7 shows that the earthquake count over the 20-year study period displays a dissimilar behavior to those in the Midwest. Despite the increase of horizontal wells, the number of earthquake events does not show a spike during the periods 2014–2018 as observed in other regions. This region shows a spike of 420 earthquake events in the year 2001. One of the main differences between the Midwest USA and California

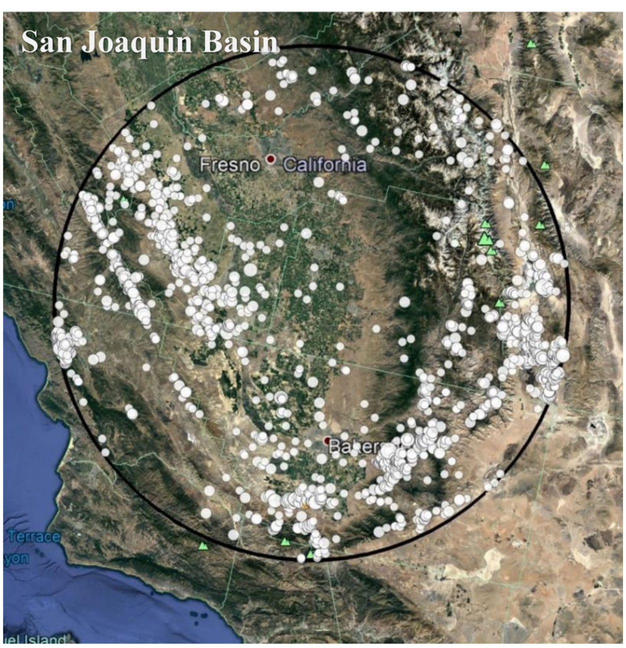

Fig. 6 Distribution of earthquakes in the San Joaquin Basin with magnitude greater than 2.5 (white dots) from 1998 to 2018 within a 150 km radius

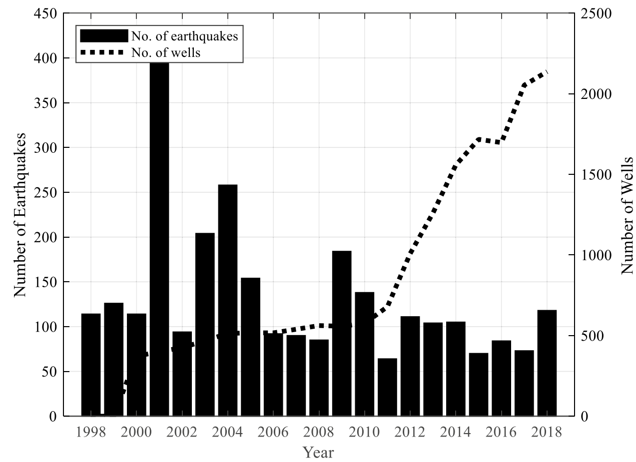

Fig. 7 Total number of earthquake events and horizontal drilling wells in San Joaquin Basin within a 150 km circle radius during the periods of 1998–2018

is the nature of earthquakes. In the Midwest USA, earthquakes occurring are of “intraplate” type, whereas earthquakes occurring in California are “interplate” type, i.e., tectonic in nature. As a result, investigating and classifying between induced events from tectonic is more complex. Goebel et al. (2015) found that while most earthquakes in Kern county are tectonic, fluid injection induces seismicity in four different cases, where three of them are connected to events above M_W 4.0. When there are sudden changes in the fluid injection rates, the probability of the induced earthquake events is 4%. In the tectonically active region, the assessment of injection-induced seismicity can affect seismicity at a distances up to 10 km or more.

Colorado and Wyoming

The Denver Basin is responsible for most of the natural gas and oil recovered from approximately 15,000 gas wells, over 90% are fracking sites (Haley et al. 2016). The Denver Basin produces 1.05 billion barrels of oil and 3.67 trillion cubic feet of natural gas per year (Higley and Cox 2007). Microseismicity in this area has been known since the 1960s due to military waste fluid disposal (Davies et al. 2013). A small cluster of earthquakes were observed in the Rocky Mountain Arsenal during 1962–1966 (Boone and Robinson 2013) due to military wastewater injection wells. In the early 2000s, earthquakes were starting to be associated with the extraction of natural gas from coal seams (Davis and Fisk 2017). In the Colorado region, recorded earthquakes (up to magnitude 5.0) were associated with high-pressure water injections (Davies et al. 2013). In the Denver Basin, there was no observed earthquake of $M_W > 2.5$ during 1998–2007 (Fig. 8). The earliest events of $M_W > 2.5$ were observed starting in 2008, with one earthquake in 2008, two earthquakes

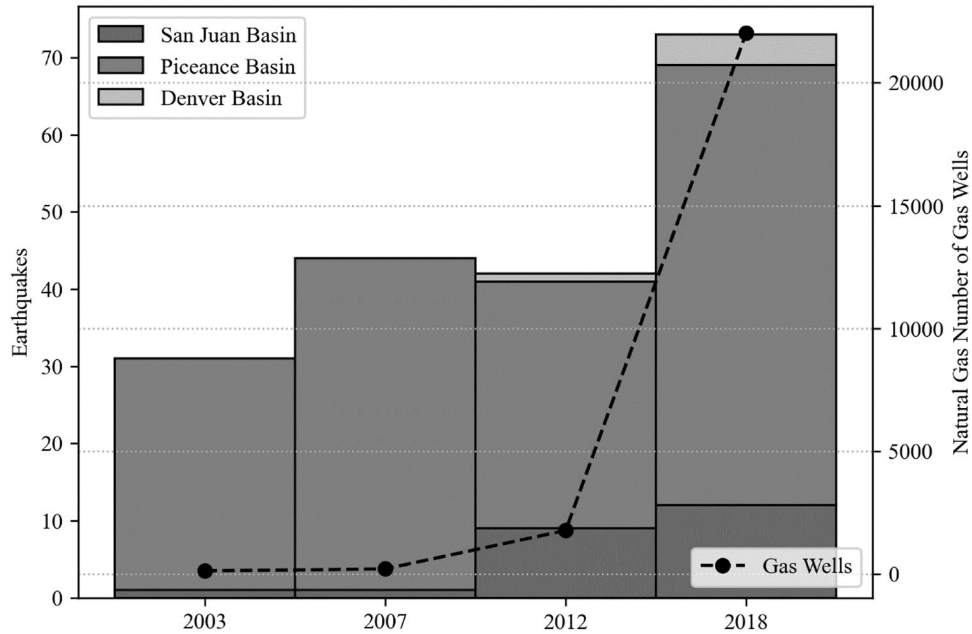

Fig. 8 Frequency of annual earthquakes recorded by Colorado regions and the number of overall horizontal wells in the state over a period range of 1998 and 2018

in 2014, followed by three earthquakes of magnitudes 2.6, 2.7 and 3.0 in the year 2016. Concurrent to this, the number of horizontal drilling wells in Colorado increased from less than 500 in the year 2008 to more than 5000 wells in the year 2016.

The Upper Green River Basin in Wyoming has large deposits of natural gas with low permeability and a history of earthquake activities (Spellman 2012). This reservoir experienced earthquake activities earlier, prior to the sudden increase in the horizontal wells. Figure 9 shows that in the locations of the epicenters in the Upper Green River Basin, the earthquake events appeared to be clustered around the mountain peaks with magnitudes ranging from 2.5 to 5.0. It should be noted that the number of wells in Wyoming is 1648, which was less than the 6000 wells in Colorado.

The San Juan and the Piceance Basin are focused on producing natural gas through horizontal wells and despite containing thousands of wells, this region is not heavily linked to induced seismicity such as those in the Midwest (Weingarten et al. 2015; Davis and Fisk 2017). During the periods 2008–2018, 11 earthquakes were observed within a 150 km radius of western-southern Colorado (Fig. 8). The earthquake activities prior and subsequently after the drilling of horizontal wells were almost same. Unlike the Midwest region, Colorado is considered as an active tectonic state, and subjected to non-induced seismicity.

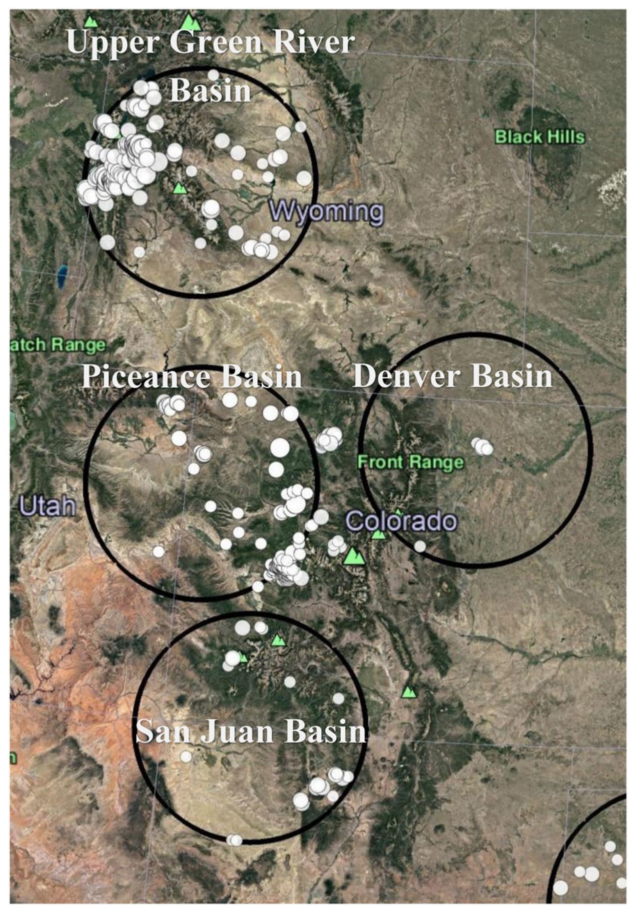

Fig. 9 Distribution of earthquakes in the Rocky Mountains with magnitude greater than 2.5 (white dots) within a 150 km radius from 1998 to 2018. The black circles cover the San Juan Basin, Denver Basin, Piceance Basin, and Upper Green River Basin

Marcellus, Michigan, and Bakken Shale

The Marcellus Shale is the largest shale formation in the USA and the second most hydro-fractured area, covering approximately 95,000 m^2 across eight states, with up to 90,000 wells (Goetz et al. 2015; Haley et al. 2016). The Marcellus Shale is the largest contributor of gas, producing about 30–40% of shale gas (Heywood 2012). In the present study, the three 150 km radius circles represent the study region for the Marcellus Shale with focus in Kentucky, West Virginia, Ohio, Pennsylvania, and New York (Fig. 10). Figure 10 shows the southern side of the Marcellus Shale, where seismicity is higher compared to the northern side of the Marcellus and Michigan Shale which have the least earthquake activities. In the Marcellus Shale, induced strike-slip and reverse faulting resulted from hydraulic fracturing and small number of earthquakes (Davies et al. 2013).

One of the most documented induced seismic events was the 2011 Youngstown, Ohio earthquake (magnitude 4.0), located in the northern center of the circle surrounding Pennsylvania. This earthquake was studied by many and it was concluded that the earthquake was induced by a NorthStar injection well, assigned to dispose the wastewater produced from fracking operations in Pennsylvania. While there were no fracking operations in the town of Youngstown, Ohio, the pressure built up from the nearby disposal well injection triggered about 109 low-magnitude earthquakes (Kim 2013; Weingarten et al. 2015). One of the reasons for the earthquake that occurred at a distance from the NorthStar injection well is likely due to the reactivation of faults nearby Youngstown, Ohio, and the injection well. The magnitude of micro-induced earthquakes is higher when faults are present in and around fracking locations. The cluster earthquakes in south-east Ohio during the periods 2011–2018 were within the proximity of oil and gas wells. Further, south of the Marcellus Shale, Gilmer County, located in West Virginia experienced no seismic events for about 15 years, but in the year 2013, two seismic clustered events (2.2 and 2.6 magnitudes) were observed. A few days prior to these seismic events, there was another event (2.7 magnitude, depth 20 km) in south-west Virginia, followed by two seismic events of magnitude >2.5 at the depth of 6–12 km within less than 0.65 km away from the horizontal well.

The Bakken Shale in North Dakota is known for its shale resources because of the huge amounts of unconventional gas trapped in the shale formation (Haley et al. 2016). This region is known to be one of the least seismically active regions in the USA. For example, during the

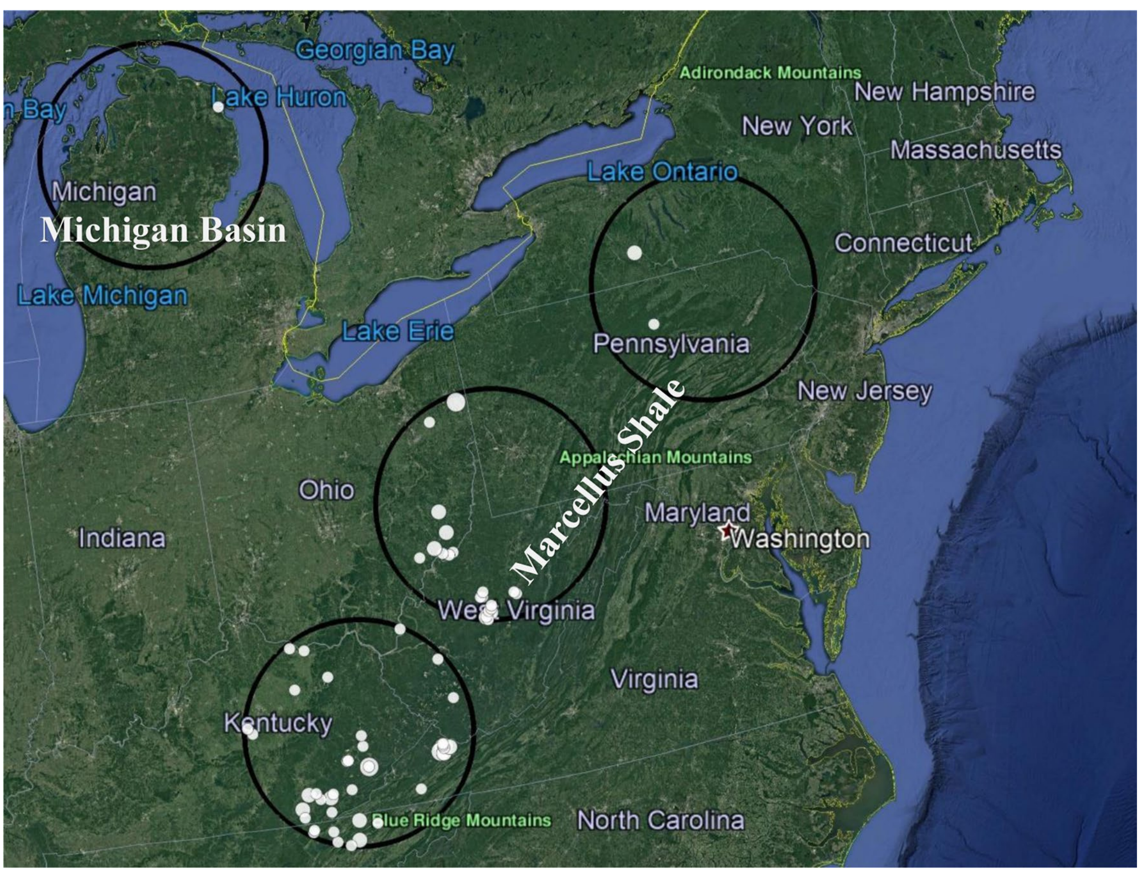

Fig. 10 Distribution of earthquakes within a 150 km radius in the Marcellus shale (comprised of the Kentucky Shale, Pennsylvania Shale, and the Alleghany Mountains) and Michigan Basin with magnitude greater than 2.5 (white dots) from 1998 to 2018

periods 1979–2018, only four seismic events of $M_W > 2.5$ were observed in the region, with one potentially being induced by oil and natural gas exploration (Frohlich et al. 2015). Like the Bakken Shale, the Michigan Shale has an extremely weak history of natural earthquakes. During the study period, only one earthquake of magnitude greater than 2.5 was observed (Fig. 10) which was induced by a mining explosion.

Conclusions

In this paper, we have discussed a statistical observation of seismic activities associated with fracking operations across the USA in the last two decades (1998–2018). Induced seismicity was observed at many fracking locations. An increase in observed seismic activity in the central USA is primarily associated with high-pressure injections and disposal wells. Using earthquake data from the USGS, we conclude that the mid-USA experiences higher induced seismicity compared to other regions especially in the Marcellus Shale Formation. Seismologically active states in the USA such as fracking sites near California and Colorado need a more complex analysis. An in-depth analysis in the present study was not possible due to non-availability of geological, geophysical, lithological, and hydrological data. However, our present analysis shows enhancement of seismic activities associated with fracking operations in locations. An exponential increase in observed seismicity is found with the increasing horizontal wells in the Texas region and an exponential relation was observed in Oklahoma, is consistent with earlier studies related to the induced seismicity in the Midwest. This difference is attributed to the difference in the geological, and geophysical settings, and injection fluid volumes.

Acknowledgements The authors are grateful to the United States Geological Survey (USGS) for making earthquake data freely available (https://earthquake.usgs.gov/earthquakes/search/) for the present study. One of us (VV) is grateful to NSF-REU program for the award of fellowship to work on Chapman University campus as SURFEE Fellow during June–August 2018. The data used in the present study from various open sources are freely available; we will be happy to provide data used in the present study to the readers. The authors thank the editor and two anonymous reviewers for their valuable comments and suggestions that have helped to improve earlier versions of the manuscript.

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