



INJECTION WELLS AND EARTHQUAKES: QUANTIFYING THE RISK

A REPORT BY ENERGY IN DEPTH
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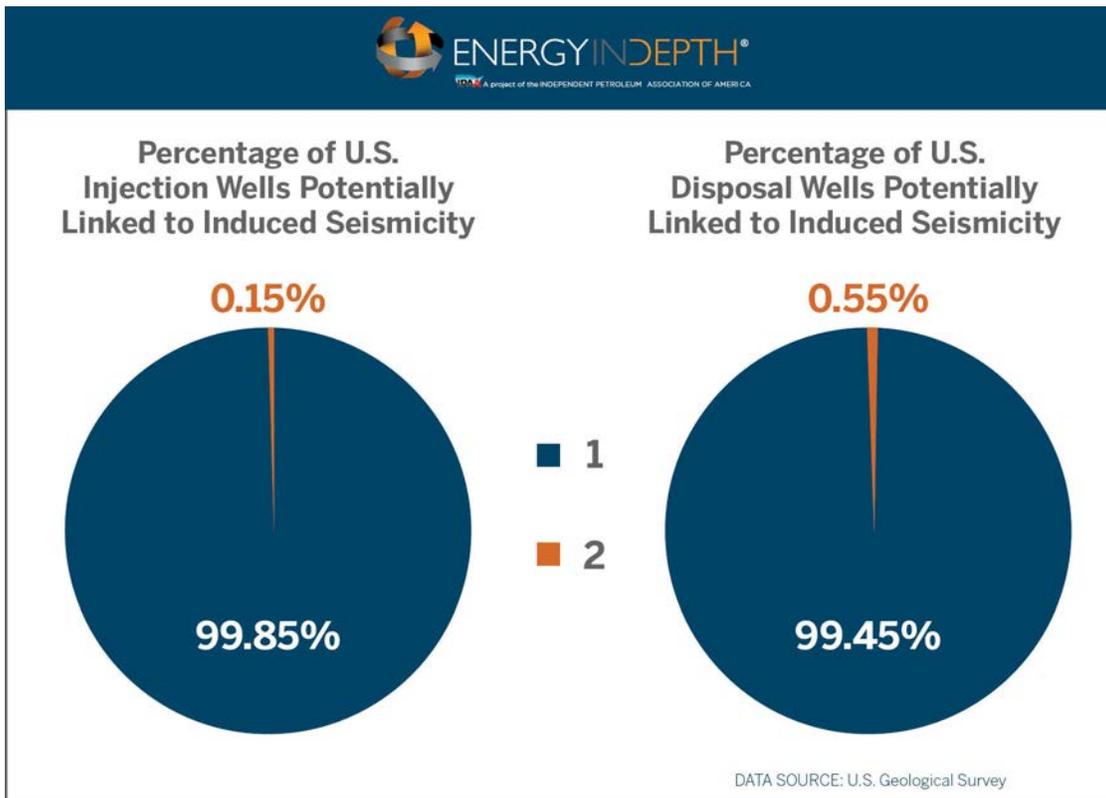
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Summary of Findings

According to the [U.S. Geological Survey \(USGS\)](#), approximately 150,000 Class II injection wells are used in connection with oil and natural gas activities across the United States. These include wells for secondary or enhanced recovery (in which wastewater is returned to the reservoir from where it originated to “enhance” the flow of hydrocarbons) as well as disposal wells, where wastewater is disposed in non-producing formations. Roughly 40,000 of these wells are designated for disposal, according to the [USGS](#).

Data from the USGS and several peer-reviewed studies show that out of an estimated 40,000 disposal wells across the United States, only 218 of them have been linked to or even suspected as a possible cause of seismicity. In other words, **only 0.15 percent of all Class II injection wells and 0.55 percent of all federally regulated disposal wells in the United States have been tangentially associated with a seismic event of any size.** This means that **99.85 percent of all the Class II wells in the United States – and 99.45 percent of all disposal wells in the United States – continue to operate without any issues whatsoever related to seismicity.**



Importantly, these numbers include *every single* well that could *even be posited as being* potentially linked to seismicity, according to peer-reviewed studies. Even if a definitive link to a particular well has not yet been scientifically established, we include it in this calculation.

Numerous peer-reviewed studies have noted that acquiring a proper understanding of induced seismicity in a sample universe this small requires knowledge of downhole pressure, volume, and location, including the orientation of faults. These studies have argued that mitigating the risk of induced seismicity requires a site by site assessment. In other words, a blanket, one-size-fits-all approach is not an appropriate solution, since wells that take on similar injection volumes and pressures may each be operating in different geologies and conditions.

The good news is that there are straightforward ways to manage the admittedly low risk of injection well seismicity, which states continue to implement. As Dr. William Ellsworth, one of USGS's leading researchers on induced seismicity, [recently said](#), “Our research strongly indicates that this is a hazard that can be

managed.” As Ellsworth also previously [explained](#), “there are really straight-forward fixes to the problem when earthquakes begin to occur.”

Introduction

Despite what [many headlines suggest](#), every bit of scientific data and information available to us today says that the risks related to seismic activity from the fracking process itself are exceedingly low. In fact, the USGS recently released [a document](#) to clear up the misrepresentation in headlines that too often link fracking to earthquakes:

“In the United States, fracking is not causing most of the induced earthquakes. Wastewater disposal is the primary cause of the recent increase in earthquakes in the central United States.”

And, as USGS [noted](#) in a separate report:

“USGS’s studies suggest that the actual hydraulic fracturing process is only very rarely the direct cause of felt earthquakes. While hydraulic fracturing works by making thousands of extremely small ‘microearthquakes,’ **they are, with just a few exceptions, too small to be felt; none have been large enough to cause structural damage.**” (emphasis added)

The National Research Council – part of the prestigious National Academies – has similarly [found](#):

“The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events.”

Hydraulic fracturing, as Stanford University’s Mark Zoback has [suggested](#), releases about “the same amount of energy as a gallon of milk falling off a kitchen counter.”

Instead, most of the concern regarding felt-seismic events relates to underground wastewater injection. There are six classes of injection wells regulated under the Environmental Protection Agency’s (EPA) [Underground Injection Control Program \(UIC\)](#), but only Class II injection wells are related to oil and gas activities. There have been a number of seismic events in the United States that scientists and regulators have suggested could have been triggered by Class II injection wells; however, they have also consistently found that seismicity from injection wells is very rare, especially when assessed in relation to the tens of thousands of injection wells operating across the country. As the USGS has recently [pointed out](#):

“Of more than 150,000 Class II injection wells in the United States, roughly 40,000 are waste fluid disposal wells for oil and gas operations. **Only a small fraction** of these disposal wells have induced earthquakes that are large enough to be of concern to the public.” (emphasis added)

The [National Research Council](#) also concluded:

“Injection for disposal of wastewater derived from energy technologies into the subsurface does pose some risk for induced seismicity, but **very few events have been documented over the past several decades relative to the large number of disposal wells in operation.**” (emphasis added)

A [major report](#) recently released by EPA, which was issued to help clarify the current state of play and actual risk profile related to induced seismicity, concluded that “**very few**” of the tens of thousands of disposal wells in the United States have produced any notable seismic activity.

As a recent study looking at the link between injection wells and seismicity from researchers at [Southern Methodist University and the University of Texas](#) noted:

“[T]ens of thousands of currently active injection wells apparently do not induce earthquakes or at least not earthquakes large enough to be felt or recorded by seismic networks.”

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To illustrate this point, consider California, a state that houses more than [52,000](#) Class II injection wells (2,919 of which are disposal wells). California [has not registered any](#) seismic activity whatsoever related to wastewater injection. On the other end of the spectrum, the state of [Connecticut](#) has [no Class II injection wells](#), yet there has been a recent uptick in recorded seismic activity throughout the state.

Oklahoma has a [long history of seismicity](#), and, according to [Reuters](#), many of the state's recent earthquakes have "occurred in the Oklahoma City metropolitan area, **where there are no high-volume wastewater injection wells.**" Oklahoma's first known earthquakes [occurred](#) in the 1800s, and another significant event occurred in 1918. As Oklahoma's state geologist Dr. Randy Keller [has noted](#), there were "zero seismograph stations prior to late 1970s" in the state, and now there are many.

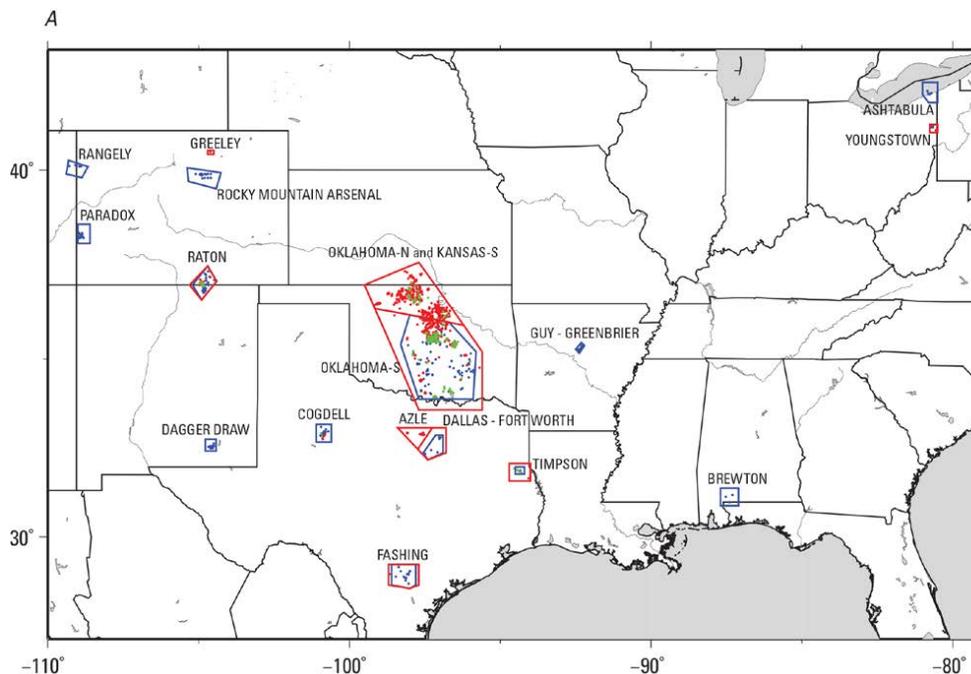
To be clear, under specific and very rare conditions, wastewater injection activities can have the effect of inducing small seismic events. Several scientific analyses have linked Oklahoma's uptick in earthquakes with wastewater disposal activities. But all this underscores why these events must be studied in the actual context in which they occur, and why blanket assumptions about all earthquakes being induced by injection activities, especially in places like Texas and Oklahoma, are incorrect, in the best case, and irresponsible in the worst.

Quantifying the Risk

So, just how many wells have been linked to felt seismicity – even if by simple correlation?

The USGS recently released [a report](#) identifying the areas of the United States where induced seismicity has potentially been linked to wastewater injection wells. Unfortunately, the report loops natural earthquakes in with seismic events that *could* have been induced by injection activities, and in one notable example, actually ascribes fault to oil and natural gas production based on source research that concludes exactly the opposite. The report also only focuses on the vague, general areas of seismicity, rather than identifying the *specific operations* under which seismic events of any size could be created.

Nevertheless, the USGS report provides valuable information for an analysis of induced seismicity. In the map below, USGS finds 17 areas within the United States that may have experienced induced seismicity:



From USGS: "Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Model—Results of 2014 Workshop and Sensitivity Studies"

According to USGS, two of those areas — Ashtabula (Ohio) and the Rocky Mountain Arsenal (Colorado) — are no longer seismically active. This leaves us with a universe of 15 active areas within the United States. That number can be further reduced by removing those clusters that have no connection to the oil and natural gas industry.

Take, for instance, Paradox Valley, Colorado. A study published in the Bulletin of the Seismological Society of America [showed](#) that nearby seismic activity was linked to a Class V injection well, which is associated with other industrial waste, and not used for oil and natural gas wastewater.

The induced seismicity at Rangely, Colo., is also a unique case and unrelated to oil and natural gas development. Rangely's seismicity was actually triggered intentionally through a scientific experiment, as a 1976 [peer-reviewed paper](#) explains. In that controlled experiment, it took increased injection at four designated wells to cause the seismicity.

Another event in Cogdell, Tex., according to a [Proceedings of the National Academy of Sciences \(PNAS\) paper](#), was not linked to water injection. As the report states:

“Water injection cannot explain the 2006–2011 earthquakes, especially as net volumes (injection minus extraction) are significantly less than in the 1957–1982 period.” (emphasis added).

With the focus currently on wastewater disposal wells and their potential connection to small seismic events, this report focuses on injection wells used for oil and natural gas wastewater in particular.

The USGS researchers include a number of other seismic events, which have not conclusively been linked to either the development of oil or gas, or the disposal of oil and gas waste. For instance, the agency includes a seismic event in the 1990s in Brewton, Ala., even though the [definitive report](#) on that seismic event — which the USGS cited — concluded, **“no clear temporal correlation between hydrocarbon recovery and the 1997 sequence has been established.”**

Nevertheless, for the purposes of this report, all active Class II injection wells taking oil and natural gas wastewater -- wherever they may be -- are included in the analysis. When we eliminate areas that are no longer active, and those that are clearly not related to the disposal of wastewater from oil and natural gas wells, we're left with 12 areas in the United States where recent seismic activity could potentially be linked to underground wastewater disposal.

Oklahoma

USGS divides the seismic activity in Oklahoma (and Kansas) into two areas: Oklahoma-South, and Oklahoma-North/Kansas-South. The seismic activity in Oklahoma has been extensively studied. A recent peer-reviewed [study](#) by researchers from Cornell University, the University of Colorado, Columbia University and the USGS found that seismic activity in Oklahoma accounts for 45 percent of magnitude 3.0 and larger earthquakes between 2008-2013 that occurred in the central and eastern United States. Yet, that increase in seismicity may be due in large part to only four wells. From the [report](#):

“Our earthquake relocations and pore pressure models indicate that four high-rate disposal wells are capable of increasing pore pressure above the reported triggering threshold (21–23) throughout the Jones swarm, and thus are capable of triggering ~20% of 2008-2013 central and eastern US seismicity.” (emphasis added)

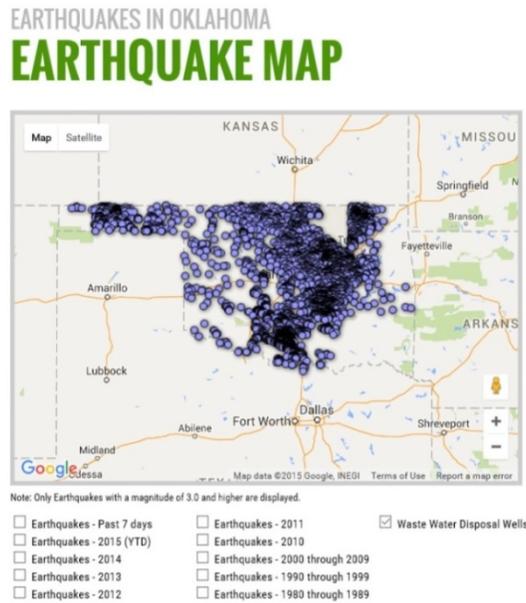
The same peer reviewed [report](#) points to 85 other individual wells that may also be related to the increase in seismicity:

“Our hydrogeological model simulated injection into the Arbuckle Group using reported injection rates at 89 wells within 50 km of the Jones swarm between 1995-2012 (14). The wells include the four high-rate wells in SE OKC and 85 wells to the northeast of Jones.”

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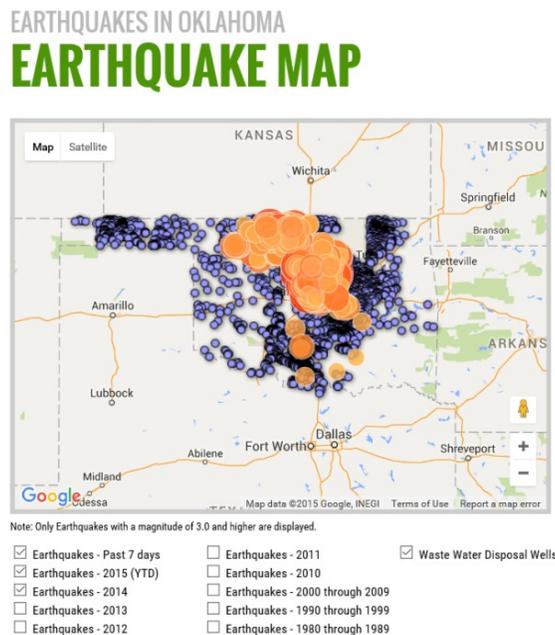
It's important to note that this study does suffer from flaws in its subsurface data and reservoir modeling, which could render its supposed linkage between injection and seismicity far weaker than described. Nonetheless, for the purposes of this report, we assume 89 wells identified in the study are at least potentially linked in some way to seismicity.

The following maps created with Oklahoma's [Interactive Earthquake Map](#) provide a visualization of Oklahoma's injection wells:



[Information Accessed on November 2, 2015](#)

This next map adds a layer, showing where all the earthquakes in 2014 and year-to-date for 2015 have been recorded:

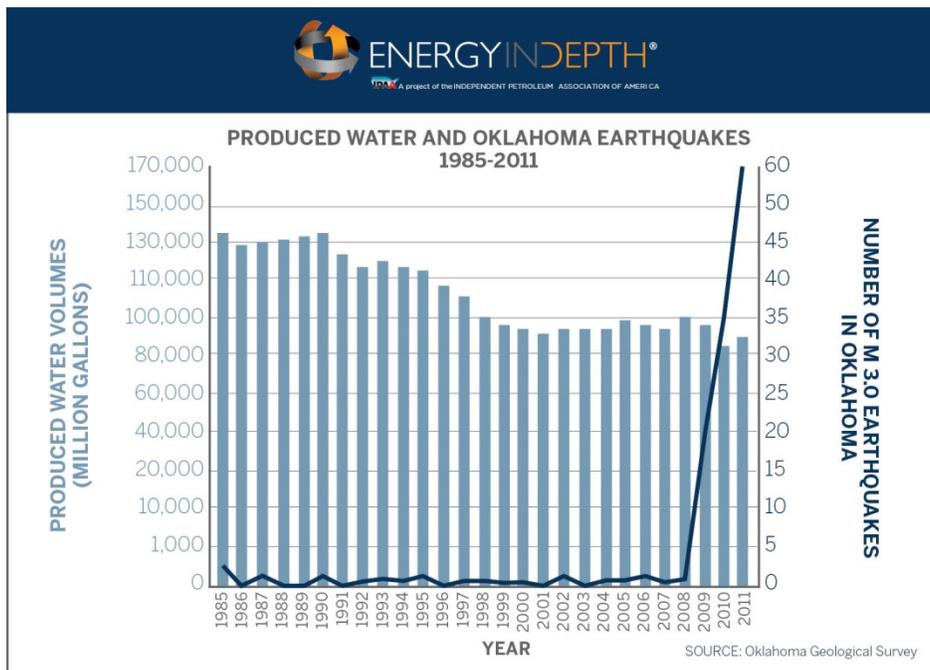


[Information Accessed on November 2, 2015](#)

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As these maps show, around 80 percent of Oklahoma's landmass is [within nine miles](#) of an injection well. Ninety-nine percent of all earthquakes recorded in Oklahoma are also within nine miles of an injection well. Some of the areas in Oklahoma, particularly in the southwestern part of the state, have high-volume injection wells, but also [few if any felt seismic events](#). Western Oklahoma has many high-volume injection sites, but not much seismic activity. Northeast Oklahoma also has many disposal wells, but almost no seismic events. In fact, there is oil and natural gas development in 70 of Oklahoma's 77 counties, but many regions of Oklahoma with the highest-densities of disposal wells – including high-volume wells – do not have any reported seismicity.

What's also important to consider is that [wastewater volumes](#) in Oklahoma were actually about 30 percent higher in the 1980s than they have been in recent years, yet there were only a handful of recorded earthquakes in Oklahoma during that earlier time. Data are sparse for that period, and some scientists have suggested that much of the water may have been injected into wells used for enhanced oil recovery (EOR). Regardless, this underscores the fact that any link between wastewater injection and seismicity is highly complex, and due to a variety of factors that are often site-specific.



Oklahoma [has more](#) than 10,789 Class II wells, including approximately 3,200 disposal wells. As stated above, peer-reviewed research has identified 89 wells in Oklahoma as being potentially linked to seismicity. However, it is possible that the number may increase as research is ongoing: In March 2015, the Oklahoma Corporation Commission (OCC) issued directives on [347 disposal wells](#) in the Arbuckle formation and about [half of them](#) were either plugged or had their volumes reduced. In July, 2015 the OCC added [211 more wells](#) to that list. Even if we assume that all 558 of those wells are potentially linked to seismicity (a big assumption to make since they are being monitored and have not yet been scientifically linked to seismicity) that would mean that 5.45 percent of Oklahoma's injection wells and 18 percent of Oklahoma's disposal wells could be linked to seismicity. In other words, even looking at the largest possible numbers from the most unlikely scenarios, the vast majority of Oklahoma wells are still operating aseismically.

Using the data from the peer-reviewed study above as a benchmark – which show 89 wells are potentially linked to seismicity – fewer than one percent (0.83 percent) of Oklahoma's Class II injection wells, and only 2.8 percent of disposal wells, have been potentially linked to seismicity. This means that 99.17 percent of class II injection wells in Oklahoma, and 97.2 percent of disposal wells are operating without seismicity.

Kansas

Injection wells have been used in Kansas since the [1930s](#), and with approximately [16,600 permitted Class II injection wells](#), including about 5,000 disposal wells, Kansas is one of the top injection-well states in the country.

The seismic events in Kansas are occurring primarily along the Oklahoma/Kansas border in Harper and Sumner Counties. Since the seismic activity is very recent, there is very little research available at this time, and no definitive link has been established between felt-seismicity and injection wells, although study is ongoing. As the Kansas Geological Survey [explains](#),

“Whether oil activities played a role has not been determined. Naturally occurring earthquakes have been recorded in the region in the past, dating back to 1956. Further understanding of the complex subsurface geology in the region is needed to estimate what impact wastewater disposal might have had.” (emphasis added)

However, earlier this year, the Kansas Corporation Commission (KCC) [required](#) companies injecting into the Arbuckle formation in Harper County and Sumner counties to reduce volumes as a precautionary measure.

There are 106 injection wells in Harper County and 164 in Sumner County. According to the KCC, about 30 percent of these wells are located in the Arbuckle formation, where producers were asked to reduce volume due to seismic activity.¹ So if we assume that every one of the 30 percent of these wells could be linked to seismicity – merely an assumption, to be sure, and one that is possibly inclusive of wells that are not inducing seismicity – then 81 wells in Kansas could potentially be linked to seismicity. Additional research may show that many of these wells are not linked to seismicity, or regulators may choose to expand the area of concern. But as with Oklahoma, it’s clear that most wells in Kansas are still operating without seismicity.

Even using the most expansive definition possible of wells that may have some connection to seismicity, we’re still left with about 0.48 percent of Kansas’ Class II injection wells, and only about 1.6 percent of disposal wells, that would fit in this category. In other words, 99.52 percent of Class II injection wells in Kansas, and about 98.4 percent of disposal wells, have not been linked to seismic activity.

Texas

USGS has identified five areas where induced seismicity could be occurring in Texas. If we set aside Cogdell, which was not related to wastewater disposal, we’re left with Azle, Dallas-Fort Worth, Fashing, and Timpson.

According to researchers at Southern Methodist University (SMU), North Texas (Azle and Dallas-Fort Worth) has experienced [four seismic “clusters” since 2008](#), the latest of which occurred around the city of Irving in 2014. As that report [explained](#):

“The first [cluster] was an earthquake sequence centered near DFW airport in 2008 and 2009 with the largest magnitude of 3.3. A second sequence from 2009 into 2010 was near Cleburne, Texas with the largest magnitude of 2.8. A third set of events occurred near Azle, Texas beginning in the Fall of 2013 and continuing through 2014 with the largest magnitude of 3.6. In all of these cases earthquakes got smaller and further apart in time following the largest events. Additional focus areas of seismicity based on USGS locations exist NE of Cleburne, near Mineral Wells and in the Venus/Midlothian area but have not been well studied.”

A [recent paper](#) by researchers at SMU, the University of Texas (UT), and the USGS concluded that “brine production combined with wastewater disposal represent the most likely cause of recent seismicity near Azle.” While there are [major flaws](#) in that study’s model simulation, and the state’s exhaustive scientific review

¹ Energy In Depth contacted the Kansas Corporation Commission (KCC) by phone to obtain this information since it is not available on KCC’s website.

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concluded the study [did not provide a conclusive link](#) between energy development and the earthquakes, the researchers linked Azle's seismic activity to only **two wells** located in the area.

The Texas Railroad Commission (RRC) recently [released findings](#) showing that injection wells were unlikely to have caused the seismic events in Azle, which [contradicts the SMU study's findings](#). However, to be conservative and for illustrative purposes, this report includes the wells in the Azle area as potentially linked to induced seismicity.

A previous [Energy In Depth report](#) on North Texas seismicity provides additional insight into injection activities in this particular region. In that report, EID noted that UT and SMU seismologists linked the Dallas Fort Worth (DFW) Airport seismic activity to a [single injection well](#). UT and SMU released a separate report on the Cleburne sequence in 2013, finding that the earthquakes "[may be related](#)" to two nearby injection wells.

Research has only just begun to come in on the Irving cluster, but there are no injection wells in proximity to the Irving quakes, with the closest one being "[more than 10 miles away](#)," according to Dr. Craig Pearson, the state seismologist for Texas. SMU researchers say the distance to the nearest disposal well is [around eight miles](#), which is still farther than the distance used to identify "nearby" wells for the Azle cluster.

A regional [study in 2012](#) by Dr. Cliff Frohlich at the University of Texas identified 17 injection wells in the Barnett Shale region that he considered to be located "near earthquakes," or within a five kilometer radius of a known epicenter.

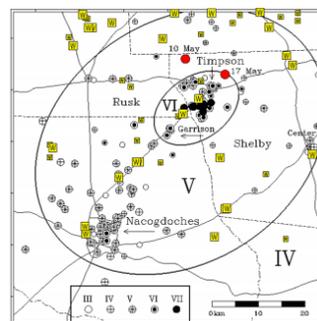
Frohlich's 2012 study was inclusive of the DFW Airport and Cleburne sequences, along with other seismic events that were identified from his more detailed analysis of USGS' transportable array data. Altogether, the extensive research in North Texas has identified approximately 18 injection wells – out of thousands in the region – that have at least a spatial relationship to earthquake activity. Frohlich has also cautioned that it's "[possible that some of these earthquakes have a natural origin](#)," though he does not believe that's the case for all of the events.

The Timpson seismic sequence includes the largest recorded earthquake in eastern Texas, a magnitude 4.8 event that occurred in 2012. Because of its magnitude, the seismic sequence has received significant attention from leading seismologists across the country, who recorded their conclusions in a recent, [peer-reviewed paper](#). The researchers acknowledge:

"(Due to earlier activity in the area) we cannot rule out the possibility that the recent seismic activity has a natural origin." (emphasis added)

However, the same team of scientists also looked at some disposal wells in the region as potential causes. The chart below from the report shows the location of disposal wells (yellow squares) and the epicenters of the biggest events in the seismic sequence (red circles). Black and white circles show the location of felt reports, as indicated by the key at the bottom left of the map.

Class II disposal wells and seismic events in Timpson, Texas



From Frohlich et al., "Investigating the cause of the 17 May 2012 M4.8 earthquake near Timpson, east Texas"

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As the same team of scientists puts it:

“There are **two high-volume injection disposal wells** within 3 km of the highest-intensity region of the Timpson earthquakes, and it is possible that injection triggered them” (emphasis added)

So, even if we assume that the Timpson seismicity is induced, only two disposal wells have been considered potential causes.

Fashing is located right in the heart of the prolific Eagle Ford formation, which, according to the [U.S. Energy Information Administration](#), yields nearly 1.8 million barrels of oil per day. As the authors of a [peer-reviewed study](#) on this cluster explain:

“Injection/production activity is nearly ubiquitous throughout much of the Eagle Ford, and in many areas this activity increased markedly in 2010. **Thus it is possible that earthquakes of natural origin may occur coincidentally near active wells.**” (emphasis added)

Unlike in other studies referenced here, the authors don't specify how many wells could potentially induce seismicity. However, they do mention that only “two of the event clusters, cluster A and cluster F, were situated within 5 km of recently active injection wells.” The map below, which displays both disposal wells (yellow dots) and seismic events, illustrates that there are only **five disposal wells within** the vicinity of the seismic activity.

Class II disposal wells and seismic events in Fashing, Texas

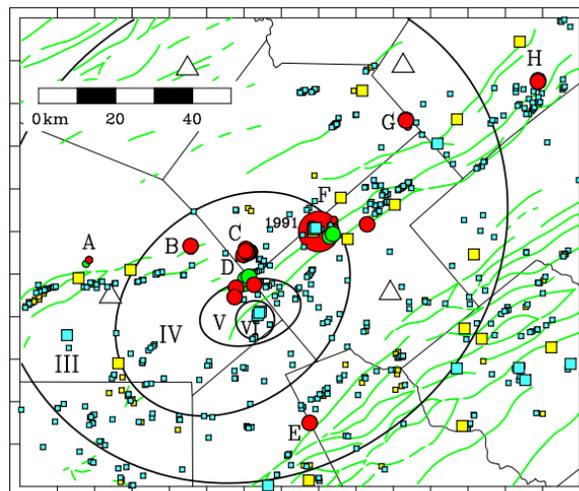


Fig. 4. For Fashing region, map of seismic events (circles, symbols as in Fig. 3), Class II injection wells (yellow squares, symbols as in Fig. 3), wells producing/extracting water (blue squares), USAArray stations (triangles), and mapped faults (green; from Ewing, 1990). Labels 'A', 'B', etc. indicate event groups listed in Table S3 and discussed in the text except for the m_b 3.6 20 July 1991 Falls City earthquake (large red symbol labeled 1991; see text for discussion). Ellipses labeled with Roman numerals III–VI are boundaries of MMI felt areas for the 20 October 2011 M_w 4.8 earthquake (see Figs. 2, 3 and Fig. S1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[Frohlich et al., “Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the \$M_w\$ 4.8 20 October 2011 earthquake”](#)

Counting the 20 wells in the Dallas Forth-Worth/North Texas area, two wells in Timpson, and the five wells in Fashing, the total number of disposal wells that are even tangentially associated with felt seismicity – even if not necessarily scientifically linked – is 27.

Texas has over 34,100 Class II wells—7,950 of them disposal wells—meaning that about 0.08 percent of Texas' Class II injection wells, and only about 0.34 percent of disposal wells, have been potentially linked to

seismicity in any form. In other words, 99.92 percent of Class II injection wells in Texas, and 99.66 percent of disposal wells have not been linked to seismicity.

Ohio

The USGS identifies two areas in Ohio that could be experiencing induced seismicity, but as noted in the introduction to this report, one of those areas (the Ashtabula cluster) is no longer considered active. That leaves only the Youngstown cluster in Ohio. As a recent [peer-reviewed paper](#) explained about the Youngstown seismic events:

“We conclude that the recent earthquakes in Youngstown, Ohio were induced by the fluid injection at a **deep injection well** due to increased pore pressure along the preexisting subsurface faults located close to the wellbore... We observe that several periods of quiescence of seismicity follow the minima in injection volumes and pressure, which may indicate that **the earthquakes were directly caused by the pressure buildup and stopped when pressure dropped.**” (emphasis added)

In other words, only one disposal well in Ohio has been potentially linked to seismic activity.

To be clear, a number of seismic events have been recorded in Mahoning County in recent years that some scientists have identified as one of the exceedingly rare cases in which a natural gas well may have caused seismic activity. The largest seismic event came in at a magnitude of 3.0, which is considered a minor seismic event in the Modified Mercalli Intensity Scale. According to the [U.S. Geological Survey](#), many people may not even recognize a 3.0 seismic event as an earthquake; the agency compares the vibrations associated with a 3.0 event to a truck passing by your house. That event caused no injuries or structural damage, according to local reports. To provide some context, Ohio has [1,026 producing Utica wells](#) and only one has been linked to seismicity.

All in all, Ohio has only had one natural gas well and one disposal well linked to seismicity. According to [the U.S. EPA](#), Ohio has 2,455 injection wells, and according to the [Department of Natural Resources of Ohio](#), 201 are disposal wells. That means that about 0.04 percent of Ohio’s Class II injection wells, and only about 0.5 percent of disposal wells, have been potentially linked to seismicity. Put another way, 99.96 percent of Class II injection wells and about 99.50 percent of disposal wells in Ohio are operating without seismicity.

Colorado

USGS observed four separate areas in Colorado that could be examples of induced seismicity. However, as mentioned in the introduction, the Rocky Mountain Arsenal is no longer active (it was also attributed to wastewater injection from nearby manufacturing operations, not oil and natural gas activities). As early as 1976, a peer-reviewed study [reported](#) that “the injection of waste fluid into the Army’s disposal well at the Rocky Mountain Arsenal was discontinued in 1966, and the earthquakes have now almost completely ceased.”

As also noted earlier, the Rangely seismic sequence was not related to oil and natural gas development, as it was a controlled experiment. What’s left, then, are the Raton Basin and the Greeley cluster.

USGS categorizes the Raton Basin, which is on the border of Colorado and New Mexico, as a New Mexico cluster (likely because most of seismic activity has occurred in New Mexico). However, because other peer-reviewed studies have found that the injection wells that could be linked to seismicity are primarily in Colorado – and may have induced a felt seismic event in Trinidad, Colorado – this report evaluates them as Colorado wells.

Authors of a Yale study [analyzed](#) two seismic events in the Raton Basin that occurred in 2001 and 2011 and [concluded](#) that only a few wells were potentially responsible. As they find in the 2001 case:

“Given that Wild Boar is the highest-rate well, began injecting shortly before earthquakes started in the area, and is the closest well to the earthquakes, it is the most likely well to have induced the earthquakes. Because PCW is a high injection-rate well and the other wells (Sawtooth, Long Canyon

and La Garita) began injecting shortly before the earthquakes started, we cannot rule out these wells as contributing to inducing the earthquakes.” (p. 13)

In other words, the researchers single out five wells that could potentially be linked to the 2001 seismic sequence. For the 2011 case, the conclusions of the peer-reviewed study are fairly similar. The authors note that:

“Although we prefer the model whereby the VPRC wells (the name assigned to three wells in the region) are primarily responsible for this earthquake sequence, the cumulative effect of all or a subset of the nearby wells (defined previously in the paper as PCW, Wild Boar, and Hill Ranch) **may have** induced these earthquakes.” (emphasis added)

In total, six wells were identified as potentially inducing seismicity in the 2011 sequence, (although two of these wells were already counted in the 2001 sequence). That means there are nine wells in total in the Raton Basin that could potentially be linked to seismicity.

As for the Greeley, Colo. cluster, in May of 2014, there was a seismic event of magnitude 3.1 and another event of 2.6 magnitude in June 2014. The [Colorado Oil and Gas Conservation Commission \(COGCC\)](#) released a report on the incident [explaining](#),

“Based on coincident timing, location, and history of injection, the SWD C4A well, operated by NGL Water Solutions, was scrutinized by the COGCC staff in conjunction with the operator. Following the June 23, 2014 earthquake, the COGCC asked NGL to shut-in the well for a period of 20 days to evaluate the well, observe seismicity during a pause in injection, and devise an injection plan going forward. After the 20 days, NGL was allowed to begin reinjecting with guidance from the COGCC. A condition for future rate-of-injection increases is that no 2.5 magnitude events within 2.5 miles of the well are observed.”

The cause of the seismic event in Greeley is still under investigation, and as the Greeley Tribune [reported](#), “it could be natural, scientists say.” However, even if the seismicity were induced, there were only two injection wells in proximity of the event. From the [Greeley Tribune](#):

“There were **two injection wells** in proximity to the epicenter of Saturday’s quake, one dug more than 8,700 feet deep and the other 10,700 feet. One is 20 years old, the other just two years old.” (emphasis added)

COGCC [reports](#) that Colorado has 920 Class II injection wells, 350 of which are disposal wells. With 11 wells potentially linked to seismicity in the state, that means that about 1.2 percent of Colorado’s Class II injection wells, and only about 3.14 percent of disposal wells, have been potentially linked to seismicity. That leaves 98.8 percent of Class II injection wells in Colorado, and about 96.86 percent of disposal wells, that are operating without seismicity.

New Mexico

Since the Raton Basin was evaluated in Colorado, there is only one other area in New Mexico that the USGS found could be potentially linked to induced seismicity: Dagger Draw.

While no recently produced peer-reviewed studies exist analyzing induced seismicity in Dagger Draw, the 1999-2004 earthquake catalogue published in the New Mexico Geology Journal did [observe](#):

“The proximity of the earthquake epicenters to **three wells** that have injected very large amounts of water at a depth of ~3.4 km **suggests** that the earthquakes are induced.” (p. 103; emphasis added)

According to New Mexico’s Oil Conservation Division, [there are](#) 5,300 active Class II wells in the state and 894 of these are disposal wells. That means that about 0.06 percent of New Mexico’s Class II injection wells, and about 0.34 percent of disposal wells have been potentially linked to seismicity. Further, 99.94 percent of Class

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II injection wells in New Mexico, and about 99.66 percent of disposal wells have not been potentially linked to seismicity.

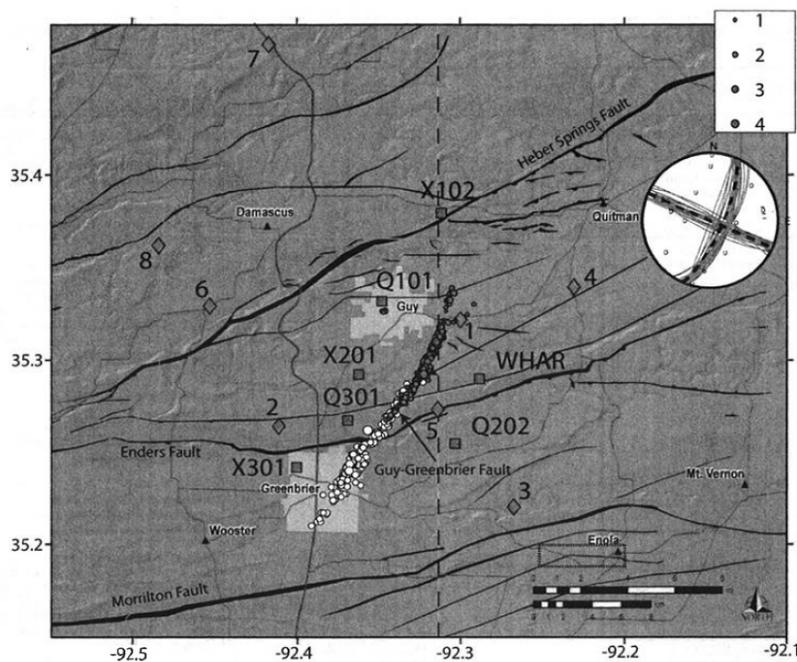
Arkansas

In Arkansas, USGS identified Guy Greenbrier as the only area in the state with induced seismicity.

[Earlier](#) peer-reviewed [studies](#) have documented that the area has a long history of seismic activity, which is unrelated to oil and natural gas development. A recent [peer-reviewed study](#) that focuses on the increase in seismic activity after 2009 explains that “the current earthquake-rate increase may simply reflect another peak in a natural cycle.”

However, the researchers note that “since the first waste disposal well became operational in April 2009, the study area has experienced an increase in the rate of magnitude, with one in 2007, two in 2008, 10 in 2009, 54 in 2010, and 157 in 2011.” The map below shows eight injection wells in the proximity of the seismic activity.

Class II disposal wells and seismic events in Guy Greenbrier



▲ **Figure 2.** Seismic stations (black squares), UIC wells (gray diamonds, Table 1), earthquakes (dark gray filled circles) between 1 October 2010 and 15 February 2011, and earthquakes (white filled circles) between 02/16/11 and 03/08/11. Named faults penetrate

[Horton et al., Disposal of Hydraulic Fracturing Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Quake](#)

The researchers explain:

“[W]astewater, a byproduct of the hydrofracking process, is being injected under pressure into subsurface rocks at **eight disposal wells** in the study area (a fairly small rectangle within Arkansas).” (emphasis added)

But, in the conclusion, the study notes that “up to **four wells** may contribute to the pore pressure in the fault zone.”

There are 813 active Class II injection wells in Arkansas and 666 of them are disposal wells. That means 0.49 percent of Arkansas’ Class II injection wells, and only about 0.6 percent of disposal wells, have been

potentially linked to seismicity. Therefore, 99.51 percent of Class II injection wells in Arkansas, and about 99.4 percent of disposal wells, are operating without seismicity.

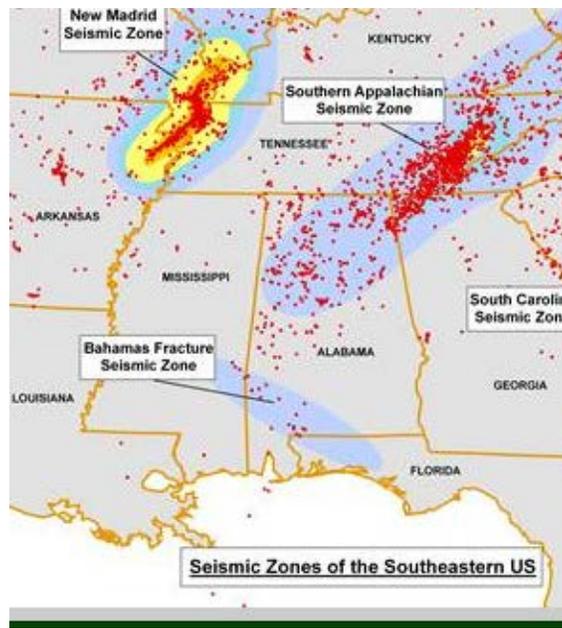
Alabama

Alabama has a long history of naturally-occurring earthquakes. As the [Geological Survey of Alabama](#) puts it:

“Four zones of **frequent earthquake activity** affecting Alabama are the New Madrid Seismic Zone, the Southern Appalachian Seismic Zone, the South Carolina Seismic Zone, and the Bahamas Fracture Seismic Zone.”

[The Geological Survey of Alabama's earthquake catalogue](#) from 1986 to 2015 lists more than 300 seismic events. As the map below from the [Geological Survey of Alabama](#) shows, most seismic events have occurred in the northern parts of the state.

Seismic events in and around Alabama



[Geological Survey of Alabama](#)

In contrast, Brewton, which USGS identifies as the only area with induced seismicity (right in the heart of the Bahamas Fracture Seismic Zone), has registered far fewer events. Importantly, the [definitive report](#) on that seismic event concluded:

“No clear temporal correlation is apparent between the 1997 Alabama earthquakes and volumes of oil and gas extracted, or in the volumes and average monthly pressures in each of the injection wells.”

The authors also note the following:

“In the five or so years preceding the 1997 earthquakes, the pressures dropped in well 77242 by ~5 MPa and in well 74112 they frequently fluctuated and increased by a factor of ~10 (Fig. 4). Such increases might be rapid enough to increase pore pressures, leading to significant pressure increases at depth.”

Although the researchers are clear that no link to seismicity has been established, they acknowledge two wells in this area that could *potentially* be linked to small earthquakes.

INJECTION WELLS AND EARTHQUAKES: QUANTIFYING THE RISK

According to the [Alabama State Oil and Gas Board](#), there are 218 active Class II wells in the state, 87 of which are disposal wells. Even though the link has not been established, if we assume that the two wells *could* be linked to seismicity, that means that about 0.92 percent of Alabama’s Class II injection wells, and only about 2.3 percent of disposal wells, have been potentially linked to seismicity. About 99.08 percent of Class II injection wells in Alabama, and about 97.7 percent of disposal wells, have not been potentially linked to seismicity.

A Fraction of One Percent

As the following chart demonstrates, at least 99.85 percent of all Class II wells in the United States – and 99.45 percent of all disposal wells – have not been linked to seismicity.

State	Number of Disposal Wells Potentially Linked to Seismicity	Total Number of Disposal Wells	Percentage of Wells Potentially Linked to Seismicity Among Disposal Wells	Total Number of Class II Wells	Percentage of Wells Potentially Linked to Seismicity Among Class II Injection Wells
Alabama	2	87	2.3%	218	0.92%
Arkansas	4	666	0.6%	813	0.49%
Colorado	11	350	3.14%	920	1.2%
Kansas	81	5,000	1.6%	16,000	0.48%
New Mexico	3	894	0.34%	5,300	0.06%
Ohio	1	201	0.5%	2,455	0.04%
Oklahoma	89	3,200	2.8%	10,789	0.83%
Texas	27	7,950	3.4%	34,100	0.08%
State Total	218	18,348	1.19%	71,195	0.31%
National	218 (all U.S. wells)	40,000 (all U.S. wells)	0.55% (all U.S. wells)	150,000 (all U.S. wells)	0.15% (all U.S. wells)

Discussion/Managing Risk

Effectively addressing induced seismicity from injection wells requires a site-specific approach, taking into account the fact that geological conditions are not uniform and similar wells in different areas may or may not have any nearby seismicity. Such an assessment should be based on downhole pressure, volumes, and location, including in particular the orientation of any nearby faults.

That’s actually something that a recent USGS report [emphasizes](#):

“In a few places, seismic activity increased as pumping began but diminished or ceased when the pumping stopped, sometimes with a lag time before the earthquake activity terminated (for example, Rocky Mountain Arsenal, Colorado). **It is important to recognize that the induced seismicity behavior differs substantially between zones**, so these rate characteristics need to be **evaluated for each zone separately.**” (p. 5; emphasis added)

In another [report](#), USGS explains it this way:

“A combination of many factors is necessary for injection to induce felt earthquakes. These include: the injection rate and total volume injected; the presence of faults that are large enough to produce felt earthquakes; stresses that are large enough to produce earthquakes; and the presence of pathways for the fluid pressure to travel from the injection point to faults.” (emphasis added)

Further, as the U.S. EPA pointed out in a [recent report](#):

“[T]he three key components behind injection-induced seismicity are (1) sufficient pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway allowing the increased pressure to communicate from the disposal well to the fault. **All three components must be present to induce seismicity.** The decision model was designed to identify the presence of any of the three key components. **Based on the historical successful implementation of the UIC program, the decision model would not be applicable to the vast majority of existing Class II disposal wells since most are not associated with seismic activity.** Use of the decision model is predicated on UIC Director discretionary authority. Federal UIC regulations do not specifically address risk consequences associated with seismicity, but allow the UIC Director discretion to ensure protection of USDWs.” (p. 27; emphasis added)

Since scientists have identified certain rare factors that need to be in place in order for felt induced seismicity to occur, the risk is manageable. As Bill Ellsworth of the USGS said [recently](#):

“We think society can manage the hazard. We don’t have to stop production of oil and gas, but we think we can do so in a way that will minimize the earthquake hazard.” (emphasis added)

Stanford geophysicist Mark Zoback also [said](#) after releasing a report on Oklahoma seismicity:

“Basically I am really optimistic. I think the scientists are making progress in understanding what is going on, they are making their findings known to regulators, and I think regulators will work with the oil and gas industry to figure out a solution.”

A good example of successfully managing the risk can be seen in the mitigation efforts at a disposal well in Greeley, Colo. In June, 2014, the Colorado Oil and Gas Conservation Commission (COGCC) temporarily [shut the well down](#) and allowed it to begin operating again one month later under [the condition](#) that injection pressures and volumes would be reduced, and that 400 feet of the well would be plugged to ensure that water didn’t flow into a nearby fault. The state also required the installation of a [seismic monitor](#), which COGCC could review, and said it would shut down the well again if problems persisted. This all proved successful. As the Associated Press in Denver [reported](#):

“The ground around a northern Colorado wastewater injection well has been relatively quiet for more than two months, offering hope that a 10-month string of more than 200 small earthquakes might have subsided.”

The Associated Press reported that Stuart Ellsworth, engineering manager for COGCC, and Anne Sheehan, a University of Colorado geology professor who has been monitoring the site, are “optimistic that shortening the well fixed the problem” and that similar efforts are underway in states like Oklahoma. Ellsworth told the AP:

“Well, I think it’s the answer,” Ellsworth said. “It was a remediation effort that reduced the risk of future events. At least that’s what it looks like.”

Statewide Efforts

Many states with instances of potentially induced seismicity are engaging in effective collaborative efforts and implementing a number of procedures to mitigate the risk.

In fact, the Interstate Oil and Gas Compact Commission (IOGCC) and the Groundwater Protection Council (GWPC) have collaborated with 38 states to develop the [StatesFirst Initiative](#), which is a “multi-state

collaboration” with the goal of “collaborating and communicating with one another in an ongoing effort to keep current with rapidly changing technology, as well as to share the very best and innovative regulatory procedures from state to state.”

One of StatesFirst’s primary focal points is induced seismicity, as is evident in its [new report](#), which takes a detailed look at the research and suggests best practices to reduce the risk. The report includes input from state regulators, seismologists, academics and industry experts from a number of different states. One of the most important takeaways from the report is that due to the fact that each well is operating under different geological conditions, efforts to mitigate induced seismicity are best handled at the state and local level. From the report:

“A one-size-fits-all approach is infeasible, due to significant variability in local geology and surface conditions, including such factors as population, building conditions, infrastructure, critical facilities, and seismic monitoring capabilities.”

Alongside collaborative multistate efforts, individual states are also taking a number of proactive steps. The Oklahoma Independent Petroleum Association (OIPA) has established an induced seismicity [working group](#) that includes operators, service companies, the Oklahoma Geological Survey and the OCC. As OIPA’s Kim Hatfield, who spearheads these efforts [stated](#):

“This workgroup is a testament to the power of cooperation between regulators, academia and industry to accomplish goals that none could achieve individually.”

Through these collaborative efforts, the industry has:

- **Invested over [\\$35 million](#)** in activities to reduce earthquake risks, since March 2015.
- Secured funds for **more seismic monitoring stations** in Oklahoma.
- Provided information on deep geological formations to state geologists, university researchers, and regulators, including **information on previously unmapped faults**.
- **Shared data with research institutions** such as Stanford University and the University of Oklahoma, which have released peer-reviewed studies on Oklahoma earthquakes.
- Helped **draft potential best practices** on wastewater disposal in coordination with the Oklahoma Geological Survey and the Oklahoma Corporation Commission (OCC).
- **Supported OCC’s recent directives and the state’s “traffic light” regulatory approach**, as recommended by the National Academy of Sciences.
- Voluntarily reduced volumes in some injection wells and shut down other salt water disposal wells in the OCCs identified areas of interest.

The cooperation of the industry has been noted by the OCC. As the AP [reported](#) recently:

“Tim Baker of the Corporation Commission said the oil and gas industry has been ‘100 percent cooperative’ as regulators attempt to pinpoint the cause of the earthquakes.”

OCC commissioner Dana Murphy [echoed](#) this sentiment, explaining to the Oklahoman:

“The industry has done a really good job of cooperating and coordinating with the Corporation Commission.”

The Oklahoma Governor’s office is also engaging in collaborative efforts. Governor Mary Fallin has formed a [Coordinating Council on Seismic Activity](#), which is continuing to study best practices in reducing potentially induced seismicity. The state has also [committed an additional \\$200,000](#) to help regulators respond to concerns about earthquakes.

INJECTION WELLS AND EARTHQUAKES: QUANTIFYING THE RISK

OCC has been working under a “traffic light system” for the past few years, which was recommended by the National Academy of Sciences. Under that system, no injection wells are permitted in “red-light” zones, or areas where seismicity is actively occurring. Under the OCC’s permitting policies, as many as 20 permit applications for injection wells in Oklahoma were never filed because they were in red-light zones, and [25 application permits were rejected](#). More than 80 permits have been held up for additional review. Wells with a “yellow-light” status are more closely monitored, which means state regulators can ask producers to reduce volumes or even shut a well down if its operation leads to seismicity. It is unclear exactly how many applications for wells in certain regions were never filed because the operator was made aware of a red-light or yellow-light status, though regulators have acknowledged that several such instances have occurred.

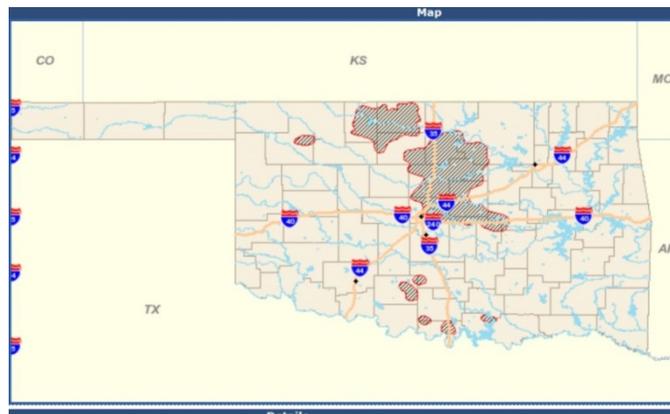
Earlier this year, the OCC increased its scrutiny for new injection wells in seismically active areas and [strengthened its oversight](#) by adding more “areas of interest” in the Arbuckle formation.

As noted earlier, the OCC specifically [asked operators](#) within areas of interest – 10 kilometers (roughly 6 miles) of a swarm epicenter—to prove their disposal wells are not disposing below the Arbuckle formation into the basement rock. The operators were asked to provide data on their wells and plug any that appear to be communicating with the Arbuckle formation by April 18. Any well operators that were unable to plug the well in that time frame were asked to reduce their volumes by 50 percent.

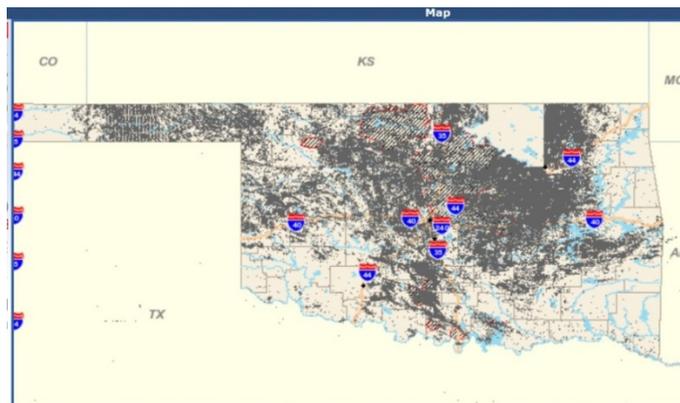
As the Oklahoman [reported](#):

“Since then, the commission said more than 50 disposal wells found to touch the basement have plugged back their depths to the Arbuckle. Another 150 disposal wells have cut their volumes in half, while other wells are keeping their volumes below 1,000 barrels per day.”

The OCC has [continued to expand](#) the number of wells it is monitoring throughout the year. The following [map](#) from the OCC shows where these “areas of interest” for seismicity are located:



This map then shows the disposal wells in the state in relation to these areas of interest:



INJECTION WELLS AND EARTHQUAKES: QUANTIFYING THE RISK

These efforts have begun to pay off. In October 2015, the director of the state Geological Survey, Jeremy Boak, said that there has been a decline in seismic activity over the past three months in Oklahoma. As the AP [reported](#):

“Boak says the average number of earthquakes of magnitude 2.8 or higher recorded in Oklahoma has dropped from five per day to 3.5 per day over the last 90 days. A dramatic drop in the price of oil over the last year has led to a decline in oil and gas drilling activity, and regulators have taken new steps to control wastewater wells, but Boak said it’s too early to draw any scientific conclusions.”

Other states have also implemented new procedures. The Texas Railroad Commission (RRC) [unanimously adopted](#) new Class II injection well rule amendments recently. According to the RRC’s [press release](#), the main components of the amendments are:

- requiring applicants for new disposal wells to conduct a search of the U.S. Geological Survey seismic database for historical earthquakes within a circular area of 100 square miles around a proposed, new disposal well;
- clarifying the Commission’s staff authority to modify or suspend or terminate a disposal well permit, including modifying disposal volumes and pressures or shutting in a well if scientific data indicates a disposal well is likely to be or determined to be contributing to seismic activity;
- allowing Commission staff to require operators to disclose the current annually reported volumes and pressures on a more frequent basis if staff determines a need for this information; and
- allowing Commission staff to require an applicant for a disposal well permit to provide additional information, including pressure front boundary calculations, to demonstrate that disposal fluids will remain confined if the well is to be located in an area where conditions exist that may increase the risk that the fluids may not be confined.

The RRC also [just announced](#) that it will hire another earthquake scientist to help evaluate applications for disposal wells in areas where seismic activity has previously occurred.

In addition to regulatory changes, Texas governor Greg Abbott recently signed [a bill](#) authorizing \$4.5 million to the University of Texas Bureau of Economic Geology to research seismic activity in Texas. Researchers at SMU were given a grant by the USGS to [begin](#) a new project of mapping faults in North Texas.

The oil and natural gas industry in Texas has been actively collaborating with state experts and other research institutions. Many of the recent studies published on this subject have benefitted from industry participation. Matthew Hornbach, a seismologist with SMU who has been studying earthquakes in North Texas, [observed earlier this year](#):

“We’re lucky that companies have been willing to work with us. They have gone far above the call of duty.”

While many of the most significant mitigation efforts have occurred in Oklahoma and Texas, other states have updated their regulations as well.

In 2014, Kansas formed a Seismicity Task Force, which includes the Kansas Geological Survey, the Kansas Department of Health and Environment, and the Kansas Corporation Commission (KCC). From the data shared in those meetings (as noted briefly), the KCC recently released [an order](#) in March 2015 requiring producers [to reduce volumes](#) injected at all wells located in the Arbuckle formation in Harper and Sumner counties. The order also states that producers cannot inject lower than the Arbuckle formation and that they must report injection pressure and volume.

In 2013, the Ohio Department of Natural Resources (ODNR) greatly expanded its [seismic monitoring capabilities](#). This effort [nearly doubled](#) the number of seismic monitors operating in Ohio, detecting all types of

seismic activity, including natural, non-felt events. The Colorado Oil and Gas Conservation Commission [requires](#) an operator to define potential faults if historical seismicity has been identified in the vicinity of a proposed disposal well.

Conclusion

As the data in this report show, the overwhelming majority of injection wells have not been linked in any way to felt seismic events.

Although the scientific community has stressed many times that the risk of induced seismicity from any given disposal well is low, this does not suggest that citizen complaints should be dismissed or ignored. For those who live in areas experiencing these events, simply suggesting that the risk is low may not adequately address concerns. However, this report hopefully provides important context for these communities as scientists, regulators and industry work together to study the risk, address it, and reduce it.

Above all, states should avoid drastic measures that are fueled more by politics than sound science, including blanket bans on injection wells, or restrictions on hydraulic fracturing, which is a separate process entirely. [Kim Hatfield](#), chairman of the Oklahoma Independent Petroleum Association's (OIPA) regulatory committee, has noted that banning wastewater injection could "completely shut down oil and gas production" in Oklahoma.

In Oklahoma, since 2010, the oil and natural gas industry has accounted for [nearly two-thirds](#) of all jobs created in the state. Roughly one in every five jobs statewide is supported by oil and natural gas development, and the industry is the "[largest single source of tax revenue](#)," according to a 2014 report prepared for the State Chamber of Oklahoma. In Texas, more than [300,000 jobs](#) have been created by the oil and natural gas industry. It has contributed over \$175 billion to the state's GDP in 2013, or about 11 percent of all industries in Texas, [according](#) to the Bureau of Economic Analysis.

Thus, any policies that ban or seriously restrict oil and natural gas development would ultimately put hundreds of thousands of people in these states out of work and deny millions of tax dollars to state and local governments. For many in Texas and Oklahoma, this "solution" would be far worse than the problem it was designed to fix.

In this report, we attempt to quantify – as definitively as we can, and using public data at every turn to do so – the risk of induced seismicity from underground wastewater disposal, demonstrating that it is actually quite low, at less than one percent of all U.S. disposal wells. Further, scientists, regulators, and industry have come together to implement a number of measures to mitigate the risk, including resource sharing to empower states to adopt practices or procedures that may have worked elsewhere, while still taking into consideration that unique geologies prevent one-size-fits-all solutions.



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