Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity

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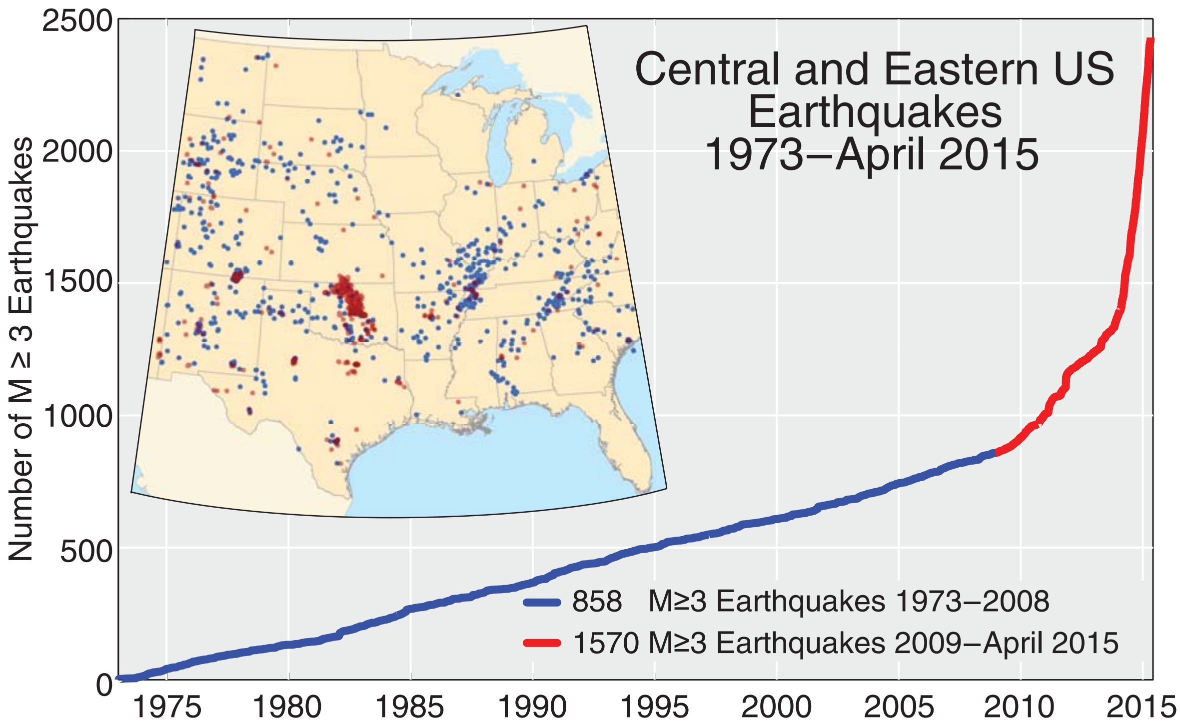
INTRODUCTION

The central United States has undergone a dramatic increase in seismicity over the past 6 years (Fig. 1), rising from an average of 24 M ≥ 3 earthquakes per year in the years 1973–2008 to an average of 193 M ≥ 3 earthquakes in 2009–2014, with 688 occurring in 2014 alone. Multiple damaging earthquakes have occurred during this increase including the 2011 **M** 5.6 Prague, Oklahoma, earthquake; the 2011 **M** 5.3 Trinidad, Colorado, earthquake; and the 2011 **M** 4.7 Guy-Greenbrier, Arkansas, earthquake. The increased seismicity is limited to a few areas and the evidence is mounting that the seismicity in many of these locations is induced by the deep injection of fluids from nearby oil and gas operations. Earthquakes that are caused by human activities are known as induced earthquakes. Most injection operations, though, do not appear to induce earthquakes. Although the message that these earthquakes are induced by fluid injection related to oil and gas production has been communicated clearly, there remains confusion in the popular press beyond this basic level of understanding.

In this article, we attempt to dispel the confusion for a nonspecialist audience. First, we highlight six common misun-



▲ **Figure 1.** Count of M ≥3 earthquakes in the central and eastern United States from 1973 to April 2015. Two abrupt increases in the earthquake rate occurred in 2009 and 2013. (Inset) Spatial distribution of earthquakes. Red dots represent earthquakes that occurred between 2009 and April 2015, and blue dots represent earthquakes that occurred between 1973 and 2008. Red color becomes brighter when there are more earthquakes in the area. The earthquake rate and distribution of earthquakes changed in 2009. Prior to 2009, earthquakes were spread across the United States. Beginning in 2009 the earthquakes are tightly clustered in a few areas (central Oklahoma, southern Kansas, central Arkansas, southeastern Colorado and northeastern New Mexico, and multiple parts of Texas).

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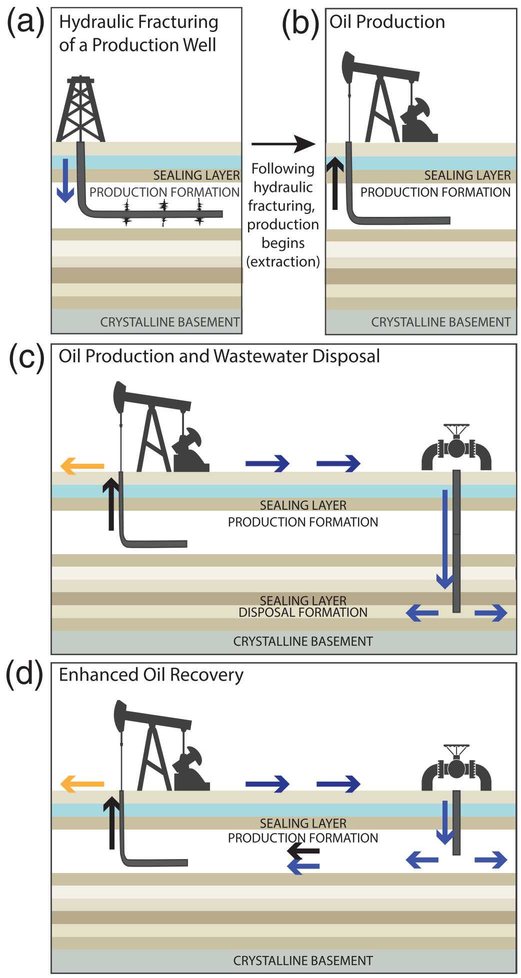
derstandings and correct them. Subsequently, we describe the three main types of fluid injection used by the oil industry: (1) hydraulic fracturing (commonly referred to as fracking), (2) wastewater disposal, and (3) enhanced oil recovery. We then explain how each of these processes can induce earthquakes. Next, we review the evidence that shows that wastewater injection is the primary cause of the large change in seismicity observed in the United States and demonstrate that this meets our expectations of how seismicity should behave. Finally, we discuss the possibility of mitigating this hazard. This article focuses on the recent seismicity induced by fluid injection; we are not aiming to provide a broad review of induced seismicity. Many articles in this vein have already been written (Nicholson and Wesson, 1990, 1992; McGarr *et al.*, 2002; Ellsworth, 2013).

COMMON MISCONCEPTIONS ABOUT FLUID INJECTION AND EARTHQUAKES

The media commonly report on induced earthquakes incorrectly, and consequently policy makers and the public have an incorrect or incomplete understanding of how and why they occur. Here, we list common misconceptions about induced earthquakes and then correct them.

1. *Misconception:* Hydraulic fracturing is causing all of the induced earthquakes.
   Correction: Hydraulic fracturing is directly causing a small percentage of the felt-induced earthquakes observed in the United States. In contrast, felt earthquakes induced during hydraulic fracturing operations are more common in western Canada. Most induced earthquakes in the United States are a result of the deep disposal of fluids (wastewater) related to oil and gas production.
2. *Misconception:* The wastewater injected in disposal wells is spent hydraulic fracture fluid.
   Correction: The amount of spent hydraulic fracturing fluid injected into wastewater disposal wells is highly variable. The fluids disposed of near earthquake sequences in Youngstown, Ohio, and Guy, Arkansas, are believed to consist largely of spent hydraulic fracturing fluid (Horton, 2012; Kim, 2013). In contrast, in Oklahoma spent hydraulic fracturing fluid represents 10% or less of the fluids disposed of in salt-water disposal wells in Oklahoma (Murray, 2013). The vast majority of the fluid that is disposed of in disposal wells in Oklahoma is produced water. Produced water is the salty brine from ancient oceans that was entrapped in the rocks when the sediments were deposited. This water is trapped in the same pore space as oil and gas, and as oil and gas is extracted, the produced water is extracted with it. Produced water often must be disposed in injection wells because it is frequently laden with dissolved salts, minerals, and occasionally other materials that make it unsuitable for other uses.
3. *Misconception:* There would be no need for wastewater disposal if hydraulic fracturing was not used.
   Correction: Salt water is produced at virtually all oil wells, whether the wells were hydraulically fractured or not. In fact, hydraulic fracturing is not used in the Hunton Dewatering Play in central Oklahoma, yet it is one of the largest producers of salt water in the United States (Walsh and Zoback, 2015).
4. *Misconception:* Induced seismicity only occurs close to the injection well and at a similar depth as injection.
   Correction: Seismicity can be induced at distances of 10 km or more away from the injection point and at significantly greater depths than injection. In the classic case of injection-induced seismicity at the Rocky Mountain Arsenal, seismicity was induced at distances of at least 10 km laterally from the well and at depths of at least 4 km greater than the depth of injection (Healy *et al.*, 1968; Herrmann *et al.*, 1981; Hsieh and Bredehoeft, 1981). More recent reports have argued that seismicity may be induced at 20 km or more from the injection point (Keranen *et al.*, 2014).
5. *Misconception:* All injection wells (hydraulic fracturing, wastewater disposal, and enhanced oil recovery) induce earthquakes.
   Correction: Most injection wells do not cause felt earthquakes. There are approximately 35,000 active wastewater disposal wells, 80,000 active enhanced oil-recovery wells, and tens of thousands of wells are hydraulically fractured every year in the United States. Only a few dozen of these wells are known to have induced felt earthquakes. A combination of many factors is necessary for injection to induce felt earthquakes. These include faults that are large enough to produce felt earthquakes, stresses that are large enough to produce earthquakes, the presence of fluid pathways from the injection point to faults, and fluid pressure changes large enough to induce earthquakes. It is likely that some of these criteria are not met in areas that have very few or no earthquakes that may be induced by wastewater injection, such as the Williston Basin in North Dakota (Frohlich *et al.*, 2015), the Michigan Basin, and the Gulf Coast of Texas and Louisiana (Weingarten *et al.*, 2015).
   More injection wells may be inducing earthquakes, but current studies are limited to the largest earthquakes and those with the best seismological and industrial data available. Further study of other earthquake sequences may reveal that additional felt earthquakes are induced. It is likely that smaller induced earthquakes are occurring and are too small to detect.
   In some sense, all hydraulic fracturing induces earthquakes, although typically microearthquakes. When production engineers hydraulically fracture, they are intentionally cracking the rock, causing microearthquakes that are typically smaller than M 0.
6. *Misconception:* Wells injecting at zero injection pressure at the wellhead (i.e., wells where the formation readily accepts fluid without requiring the fluid to be pushed into the formation) cannot induce earthquakes.
   Correction: Wells injecting under gravity feed (i.e., wells where you can pour fluid down the well without added pressure) increase the fluid pressure within the injection formation and thus can induce earthquakes. For example,



▲ **Figure 2.** Simplified diagrams of oil-field operations. The geology in these diagrams is simplified from natural situations in which there are many more rock layers. Arrows show the directions of fluid being injected or withdrawn. Arrow color indicates the contents of the fluid: black (oil, gas, and wastewater), yellow (oil and gas), and blue (wastewater). (a) For a period of hours to days, fluids are injected at high pressure into a production well. The pressures are high so that the rock surrounding the well fractures and the permeability is increased. Increased permeability allows the extraction of oil or gas from a larger region. This technique of high-pressure injection is known as hydraulic fracturing. Following the hydraulic fracturing of a well, the well goes into production. (b) Production wells extract oil and gas from the ground. Some, but not all, production wells are hydraulically fractured. (c) Production wells extract oil and gas, and as a byproduct, salt water. The salt water is found in the same formation as the oil and gas and is commonly termed "produced water." The oil and gas are separated from the produced water, and the produced water is injected into a deeper formation with the disposal well. In practice, the wastewater from many production wells is injected into a single injection well. (d) An alternative to wastewater disposal is enhanced oil recovery. In enhanced oil recovery, produced water is injected into the formation holding the oil and gas. The injection of produced water is intended to sweep oil and gas that is close to the injector toward the production wells to enhance oil recovery.

the vast majority of wells in the Raton Basin are injecting under gravity feed and have induced an earthquake sequence that is ongoing since 2001 and includes an **M** 5.3 earthquake and an **M** 5.0 earthquake (Barnhart *et al.*, 2014; Rubinstein *et al.*, 2014).

INDUCED VERSUS TRIGGERED

Earthquakes stimulated by human activities are commonly referred to as being either induced or triggered. As originally proposed by McGarr *et al.* (2002), induced should be used for earthquakes where human-introduced stresses are similar in amplitude to the ambient stress state, and triggered should be used for earthquakes where human-introduced stresses are only a "small fraction of the ambient level." In the seismology community, triggered has an additional meaning: earthquakes caused by earlier earthquakes are triggered by the previous earthquake (Freed, 2005). This process applies to natural and man-made earthquakes alike. To avoid any confusion between the two kinds of triggered earthquakes, we suggest using induced exclusively to describe all anthropogenic earthquakes, and we have done so in this article. Accordingly, triggered refers to the physical interaction between parent and daughter events, whether natural or anthropogenic in origin.

HYDRAULIC FRACTURING

Invented in 1947 (Hubbert and Willis, 1957), hydraulic fracturing (often colloquially referred to as fracking), is a technique that has been used for decades in the oil and gas industry. Approximately one million wells were hydraulically fractured in the United States between 1947 and 2010 (Gallegos and Varela, 2014). Hydraulic fracturing is a technique that aims to improve the production of wells by increasing the number of and extending the reach of fluid pathways (i.e., fractures) between the formation and the well. Hydraulic fracturing achieves this by injecting fluid, typically water, at high pressure into low-permeability rocks, such that the fluid pressure fractures the rocks or stimulates slip across pre-existing faults or fractures (Fig. 2a). Increasing the fracture density and extent of the fracture network enhances fluid flow and allows for more distant fluids to be accessed by a well. In addition to fluid, a propping agent (e.g., sand) is injected to keep the newly formed fractures open. Following hydraulic fracturing, which takes a few hours to a few days, there is a period where the hydraulic fracturing fluid is allowed to flow back to the surface where it is collected for disposal, treatment, or reuse. Subsequent to flow back, the wells begin production (i.e., the extraction of oil or gas begins) (Fig. 2b).

At first, vertical oil wells were hydraulically fractured to increase production. Then, in the 1990s, extended reach horizontal drilling technology was developed. This allowed drillers to steer wells more precisely such that they could remain within narrow horizontal and subhorizontal oil and gas reservoirs over great distances. This enabled production along the length of the well within the production formation. This technology, combined with hydraulic fracturing, unlocked gas and oil resources in tight formations (e.g., shales) and is largely responsible for the recent boom in gas and oil production in the United States.

In some sense, hydraulic fracturing is intended to cause earthquakes, albeit very small, in that the intent is to fracture the rock. These intentionally produced earthquakes, often termed microseismic events, are typically on the order of $-3.0 \le M \le 0$ (Warpinski *et al.*, 2012). In cases when hydraulic fracturing induces earthquakes of larger magnitudes, the earthquakes are likely the result of the reactivation of nearby pre-existing faults (Maxwell *et al.*, 2010). Despite being invented in 1947, the first report of a felt hydraulic fracturing-induced earthquake was in 1991 (Kanamori and Hauksson, 1992). Since 2011, a number of other earthquake sequences with felt earthquakes induced by hydraulic fracturing have been reported (Green *et al.*, 2012; Holland, 2013; Friberg *et al.*, 2014; Skoumal *et al.*, 2015). The largest hydraulic fracturing-induced earthquakes to date are two M_L 4.4 earthquakes in central west Alberta and northeast British Columbia (BC Oil and Gas Commission, 2014). In these cases, the total injected volumes were remarkably high for hydraulic fracturing (e.g., 630,000 barrels or $100,000 \text{ m}^3$ for both M_L 4.4 earthquakes; H. Kao, personal comm., 2015).

WASTEWATER DISPOSAL

Waste fluids are often a byproduct of many oil and gas extraction operations. At times these fluids can be cleaned and reused or applied for other purposes. In other instances they are unsuitable for other uses and must be disposed. When waste fluids must be disposed, they are often injected deep underground into high-permeability formations, usually deeper than the production reservoirs, for permanent sequestration and isolation from oil/gas reservoirs and drinking-water aquifers (Fig. 2c). The wells in which these fluids are disposed are known as wastewater wells or salt-water disposal wells. Underground disposal of wastewater has a lengthy history because it is typically considered an economic and safe option (Ferguson, 2015).

The contents of wastewater can be highly variable. In some places, it is primarily spent hydraulic-fracturing fluid (e.g., Ohio and Arkansas), whereas in other locations wastewater often consists mostly of formation brines that come to the surface at the same time as the oil and gas that is extracted. For instance, in Oklahoma, only 10% of the fluid injected into disposal wells is spent fluid that was initially used in hydraulic fracturing and cannot be reused (Murray, 2013). These formation brines (also termed produced water or wastewater) are typically salt water that is trapped in the same pore space as the oil and gas and comes up with the oil and gas. This salt water is often laden with dissolved salts, minerals, and occasionally other materials that make it unsuitable for other uses.

Injection rates of disposal wells range widely, with some wells injecting 100 barrels (16 m^3)/month and other wells with rates exceeding one million barrels ($160,000 \text{ m}^3$)/month.

The Denver earthquakes of the 1960s, caused by injection of chemical waste at the Rocky Mountain Arsenal, were the first earthquakes to be identified as related to deep, underground injection (Evans, 1966; Healy *et al.*, 1968). The largest earthquake in the sequence was **M** 4.9 (Herrmann *et al.*, 1981). Many more injection-induced earthquakes have been identified since this sequence, the largest being the August 2011 **M** 5.3 Trinidad, Colorado, earthquake (Rubinstein *et al.*, 2014) and the November 2011 **M** 5.6 Prague, Oklahoma, earthquake (Keranen *et al.*, 2013).

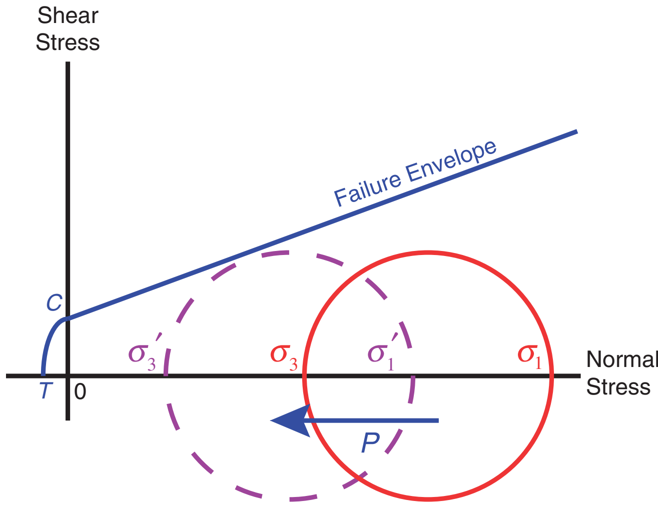
ENHANCED OIL RECOVERY

Enhanced oil recovery is a suite of injection techniques used by the oil and gas industry to allow or encourage more oil and gas to be produced from a reservoir than would come out on its own (Murray, 2013) (Fig. 2d). The techniques typically involve the injection of water, steam, or carbon dioxide into the production formation. Water flooding (the injection large amounts of water) improves production by sweeping the oil and gas toward the production wells. The injection of steam and carbon dioxide is undertaken to improve production by reducing the viscosity of oil. Enhanced oil-recovery operations typically aim to keep the fluid pressure in the reservoir at or below its original level.

Many cases of enhanced oil recovery-induced earthquakes have been identified (see Nicholson and Wesson, 1992 and references therein). In fact, one of the best documented cases of injection-induced earthquakes was from water flooding near Rangely, Colorado (Gibbs *et al.*, 1973; Raleigh *et al.*, 1976). Because this field had an extensive history of induced earthquakes from enhanced oil recovery, it was selected for an experiment in earthquake control by the U.S. Geological Survey. Raleigh *et al.* (1976) demonstrated that by varying the fluid pressure at depth, they could control whether or not earthquakes were induced. The largest earthquake known to be induced by enhanced oil recovery is an **M** 4.6 earthquake in the Cogdell field near Snyder, Texas (Gan and Frohlich, 2013).

MECHANISM OF INDUCED SEISMICITY

There are many ways in which human activities induce earthquakes (e.g., reservoir impoundment, fluid injection, fluid extraction, and mining). Each of these actions fundamentally causes earthquakes in the same way: they change the stress conditions on faults, which can facilitate failure. Fluid injection can induce earthquakes in four different ways: (1) the injection of fluids raises pore-fluid pressure within a fault, (2) the injection of fluids fills and compresses fluids within pore spaces causing deformation (poro-elastic effects), (3) the injection of fluid that is colder than the rock into which it is being injected into causes thermoelastic deformation, and (4) fluid



▲ **Figure 3.** Mohr circle diagram showing the effect of increased fluid pressure on a fault. Normal stress on the horizontal axis (compression when positive and tension when negative) and shear stress on the vertical axis. The maximum and minimum normal stresses acting in any given location are plotted as σ_1 and σ_3, and a Mohr circle (shown in red) is drawn to represent the range of stresses acting on a plane at one location, showing both the shear and normal stress at a given location. When fluid pressure (P) is increased, normal stresses are reduced by P, resulting in new normal stresses σ_1' and σ_3', moving the Mohr circle to the left by P (purple). This also means that the Mohr circle is closer to the failure envelope and makes shear or tensile failure more likely. The blue line represents the failure envelope with the slope being equal to the frictional resistance at that point on the plane. When the stress conditions exceed the shear strength of the fault, slip on that fault may occur. The failure envelope is computed as the sum of the cohesion C (an intrinsic property of an individual rock) and frictional resistance (resistance to slip on a fault). When the minimum principal normal stress σ_3 is less than T, the tensile strength of the rock, the rock will fail in tension, that is, cracks will open. Figure after figure 7 in Maxwell (2013).

injected adds mass to the injection formation. Observations and numerical modeling indicate that increased fluid pressure within faults most strongly influences whether an injection well will induce earthquakes (Raleigh *et al.*, 1976; Shapiro and Dinske, 2009; McClure and Horne, 2011).

It is critical to note that the injected fluids need not travel the entire distance from the injection well to a fault for the injection to affect the fault's behavior. Injection can affect a fault's behavior via the change in fluid pressure, which can be transmitted greater distances than fluids themselves. Like stepping on the brakes in a car, the increase in the fluid pressure that is initiated at the well (or brake pedal) is transmitted to the fault (brakes) without the fluid traveling the full distance between the well and fault.

As fluid is injected into a reservoir, the fluid pressure within that reservoir rises. If this fluid pressure increase is transmitted to a fault, the increase in pore pressure counteracts the stresses holding the fault closed (the normal stress), resulting in a lower effective stress. With lower effective normal stress clamping a fault, the frictional resistance to slip is lower and the fault is more prone to slip. The effect of fluid injection on fault failure is illustrated with a Mohr-Coulomb diagram, which shows a failure envelope for a typical compressive medium (Fig. 3). As pore pressure increases, the Mohr circles shift to the left and closer to the failure envelope. If the faults are suitably oriented with respect to the local stress field, they may slip and cause earthquakes.

In addition to the fluid pressure in candidate faults, there are many other factors that influence whether or not injection will induce earthquakes. These include injection parameters (e.g., cumulative injected volume, injection rate, injection pressure, fluid temperature, and injection depth) and reservoir conditions (e.g., pore pressure, temperature, rock strength, the presence of pre-existing faults and their orientation relative to the local stress field, and reservoir permeability; Shapiro and Dinske, 2009; Zoback, 2012). Many of these parameters are not easily constrained or are unknown, which makes it difficult to determine the wells that will induce earthquakes and those that will not. Most often, faults reactivated by injection activities were unmapped before the earthquakes illuminated them.

WHICH METHOD OF FLUID INJECTION HAS THE HIGHEST LIKELIHOOD OF INDUCING DAMAGING EARTHQUAKES?

Hydraulic fracturing, long-term wastewater injection, and enhanced oil recovery have all induced earthquakes in the United States and Canada in the past few years (Horton, 2012; Gan and Frohlich, 2013; Holland, 2013). As discussed above, wastewater disposal is responsible for the vast majority of the increase, including the largest and most-damaging induced earthquakes (Horton, 2012; Keranen *et al.*, 2013; Frohlich *et al.*, 2014; Rubinstein *et al.*, 2014). Here, we explore why wastewater disposal is responsible for this change.

It is probable that the duration of injection, the magnitude of the fluid pressure increase, and the size of the region affected by injection will strongly influence whether earthquakes will be induced and how large they will be. Larger fluid pressure changes are more likely to induce earthquakes than smaller pressure changes, larger volumes of injected fluid increase the probability of a large fault being affected by the fluid pressure change, and a longer duration of injection gives earthquakes a longer time window during which they can nucleate.

A quick examination of the above factors suggests that wastewater injection into previously undisturbed formations is more likely to induce felt earthquakes than hydraulic fracturing. Although the higher injection pressures suggest that hydraulic fracturing would be more likely to induce earthquakes than wastewater disposal, the duration of injection and the total volume of injection of hydraulic fracturing is much smaller than wastewater disposal. Wastewater disposal wells typically operate for years or decades, whereas hydraulic fracturing lasts for days. Wastewater disposal wells also inject far more fluid than hydraulic fracturing, so they affect a much larger region. The largest hydraulic fracturing treatments inject approximately 250,000 barrels (Gallegos and Varela, 2014) over the course of a few days; in the United States there are well over 1000 disposal wells that inject 100,000 barrels/month or more (Weingarten *et al.*, 2015). Within a matter of months, all of these wastewater disposal wells will greatly exceed the volumes injected by even the largest hydraulic-fracturing operations, which implies that they are more likely to induce earthquakes. By virtue of its longer duration and larger injection volumes, wastewater injection is more likely to induce earthquakes at a greater distance and over a longer time span than hydraulic fracturing and thus, is a much more important source of induced earthquakes than hydraulic fracturing.

Wastewater injection into undisturbed formations is also more likely to induce earthquakes than injection for enhanced oil recovery. The durations and volumes for both kinds of wells are similar. The difference between these wells is that enhanced oil recovery injects large volumes of fluid into depleted reservoirs where oil and gas have already been extracted and recycles produced water such that the pressure within the injection reservoir rarely exceeds the preproduction level. In contrast, wastewater injection is injected into virgin formations and thus raises the pore pressure from their initial levels. Avoiding pore-pressure increases within reservoirs reduces the likelihood of enhanced oil-recovery operations inducing earthquakes.

These considerations are in accord with observations. Wastewater injection is associated with all of the largest injection-induced earthquakes (Horton, 2012; Frohlich *et al.*, 2014; Keranen *et al.*, 2014; Rubinstein *et al.*, 2014), and there are many more reported cases of wastewater injection-induced earthquakes in the past five years in the United States alone (Frohlich *et al.*, 2011, 2014; Frohlich, 2012; Justinic *et al.*, 2013; Kim, 2013; Block *et al.*, 2014; Keranen *et al.*, 2014), and yet there are only approximately 35,000 wastewater disposal wells that are active in the United States. This is in contrast to hydraulic fracturing, which is far more common (~1.8 million treatments over ~1 million wells, 1947–2010 in the United States; Gallegos and Varela, 2014) than wastewater disposal wells, and yet there are only three reported cases of hydraulic fracturing-induced earthquakes in the United States (Holland, 2013; Friberg *et al.*, 2014; Skoumal *et al.*, 2015) and only a few more worldwide (BC Oil and Gas Commission, 2012, 2014; Green *et al.*, 2012; Farahbod *et al.*, 2015). Likewise, enhanced oil recovery is quite common (~80,000 active wells United States; Weingarten *et al.*, 2015), yet there are few recent earthquakes associated with it (Gan and Frohlich, 2013).

Results from modeling analyses also support the notion that wastewater injection is more likely to induce large earthquakes. The injection pressure, pressure within the field, duration of injection, and volume of rock affected by injection all influence the likelihood of inducing earthquakes (Langenbruch and Shapiro, 2010; Bachmann *et al.*, 2011; McClure and Horne, 2011).

WHY NOW?

The recent increase in injection-induced seismicity is caused by a corresponding increase in wastewater disposal in the central United States. The earthquake rate increase in Oklahoma, where the vast majority of the increase has occurred (585 of 688 $M \geq 3$ earthquakes in the central United States in 2014), corresponds to a doubling of the wastewater disposal rate in the state from 1999 to 2013 (Walsh and Zoback, 2015). Focusing on the areas of increased seismicity within Oklahoma, we find that injection increased by factors of 5–10 (Walsh and Zoback, 2015). Other areas of increased rates of induced earthquakes also experienced sudden increases in wastewater disposal (Frohlich, 2012; Horton, 2012; Frohlich *et al.*, 2014; Keranen *et al.*, 2014; Rubinstein *et al.*, 2014).

SUMMARY AND OUTLOOK

Although enhanced oil recovery and hydraulic fracturing have been implicated in some recent seismicity, studies indicate that the majority of the increase in seismicity is induced by the deep disposal of fluids produced by oil and gas production (wastewater disposal). Hydraulic fracturing does not play a key role in the increase in that (1) hydraulic fracturing does not typically induce felt earthquakes; (2) in Oklahoma, the location of the largest increase in seismicity, spent hydraulic fracturing fluid does not represent a large percentage of the fluids comprising disposed wastewater; and (3) oil produced from many fields with large volumes of produced water did not involve any hydraulic fracturing. Similarly, enhanced oil recovery does not play a major role in the increase in seismicity, likely because operators attempt to keep fluid pressures in the reservoir balanced with the fluid pressure prior to production. Accordingly, wastewater disposal is responsible for inducing the majority of the earthquakes. Increased fluid pressure is the probable driving mechanism to induce earthquakes, and of the three aforementioned processes, wastewater disposal wells can raise fluid pressures more, over longer periods of time and over larger areas, than either of the other injection methods.

Although seismicity associated with salt-water disposal has caused damaging earthquakes, we have not yet seen a catastrophic event or fatalities. Preliminary results in a number of areas of induced seismicity indicate that the earthquake hazard in these areas is comparable to the hazard in areas more traditionally known for earthquakes, such as California (Petersen *et al.*, 2015). The increase in hazard is undoubtedly of concern and efforts to assess the hazard from induced earthquakes are ongoing. Fortunately, some authors have suggested that there is hope for mitigating the likelihood of damaging earthquakes through detailed seismic monitoring, careful selection of injection locations, variation of injection rates and pressures in response to ongoing seismicity, and a clear management plan (Zoback, 2012; McGarr *et al.*, 2015; Walters *et al.*, 2015). Mitigation of hazard from future-induced events, however, requires a detailed understanding of the physical processes involved in inducing large magnitude events and a detailed understanding of the geology and hydrology at the site of the earthquakes. To reach this goal, three kinds of data will be necessary: (1) seismic data: high-quality, real-time earthquake locations, which require dense seismic instrumentation; (2) geologic data: hydrological parameters, orientation and magnitude of the stress field, and the location and orientation of known faults; and (3) industrial data: injection rates and downhole pressures sampled and reported frequently. Managing the likelihood of induced earthquakes is an ambitious, but possible task that will require collaboration between scientists, industry, and regulators.

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REFERENCES

Bachmann, C. E., S. Wiemer, J. Woessner, and S. Hainzl (2011). Statistical analysis of the induced Basel 2006 earthquake sequence: Introducing a probability-based monitoring approach for Enhanced Geothermal Systems, *Geophys. J. Int.* **186,** no. 2, 793–807, doi: 10.1111/j.1365-246X.2011.05068.x.

Barnhart, W., H. Benz, G. P. Hayes, J. L. Rubinstein, and E. Bergman (2014). Seismological and geodetic constraints on the 2011 M_w 5.3 Trinidad, Colorado earthquake and induced deformation in the Raton Basin, *J. Geophys. Res.* **119,** doi: 10.1002/2014JB011227.

BC Oil and Gas Commission (2012). *Investigation of Observed Seismicity in the Horn River Basin*.

BC Oil and Gas Commission (2014). *Investigation of Observed Seismicity in the Montney Trend*.

Block, L. V., C. K. Wood, W. L. Yeck, and V. M. King (2014). The 24 January 2013 M_L 4.4 earthquake near Paradox, Colorado, and its relation to deep well injection, *Seismol. Res. Lett.* **85,** no. 3, 609–624, doi: 10.1785/0220130188.

Ellsworth, W. L. (2013). Injection-induced earthquakes, *Science* **341,** doi: 10.1126/science.1225942.

Evans, D. (1966). The Denver area earthquakes and the rocky mountain arsenal disposal well, *The Mountain Geologist* **1,** no. 1, 23–36.

Farahbod, A. M., H. Kao, D. M. Walker, and J. F. Cassidy (2015). Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia, *Can. J. Earth Sci.* **11,** 1–11.

Ferguson, G. (2015). Deep injection of waste water in the western Canada sedimentary basin, *Groundwater* **53,** no. 2, 187–194, doi: 10.1111/gwat.12198.

Freed, A. M. (2005). Earthquake triggering by static, dynamic, and post-seismic stress transfer, *Annu. Rev. Earth Planet. Sci.* **33,** no. 1, 335–367, doi: 10.1146/annurev.earth.33.092203.122505.

Friberg, P. A., G. M. Besana-Ostman, and I. Dricker (2014). Characterization of an earthquake sequence triggered by hydraulic fracturing in Harrison County, Ohio, *Seismol. Res. Lett.* **85,** no. 6, doi: 10.1785/0220140127.

Frohlich, C. (2012). Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas, *Proc. Natl. Acad. Sci. Unit. States Am.* **109,** no. 35, 13934–13938, doi: 10.1073/pnas.1207728109.

Frohlich, C., W. Ellsworth, W. A. Brown, M. Brunt, J. Luetgert, T. MacDonald, and S. Walter (2014). The 17 May 2012 M 4.8 earthquake near Timpson, East Texas: An event possibly triggered by fluid injection, *J. Geophys. Res.* **119,** no. 1, 581–593, doi: 10.1002/2013JB010755.

Frohlich, C., C. Hayward, B. Stump, and E. Potter (2011). The Dallas-Fort Worth earthquake sequence: October 2008 through May 2009, *Bull. Seismol. Soc. Am.* **101,** no. 1, 327–340, doi: 10.1785/0120100131.

Frohlich, C., J. I. Walter, and J. F. W. Gale (2015). Analysis of transportable array (USArray) data shows earthquakes are scarce near injection wells in the Williston Basin, 2008–2011, *Seismol. Res. Lett.* **86,** no. 2A, 1–8, doi: 10.1785/0220140180.

Gallegos, T. J., and B. A. Varela (2014). Trends in hydraulic fracturing distributions and treatment fluids, additives, proppants, and water volumes applied to wells drilled in the United States from 1947 through 2010: Data analysis and comparison to the literature, *U.S. Geol. Surv. Sci. Investig. Rep. 2014-5131*.

Gan, W., and C. Frohlich (2013). Gas injection may have triggered earthquakes in the Cogdell oil field, Texas, *Proc. Natl. Acad. Sci. Unit. States Am.* 1–6, doi: 10.1073/pnas.1311316110.

Gibbs, J., J. Healy, C. Raleigh, and J. Coakley (1973). Seismicity in the Rangely, Colorado, area: 1962–1970, *Bull. Seismol. Soc. Am.* **63,** no. 5, 1557–1570.

Green, C. A., P. Styles, and B. J. Baptie (2012). *Preese Hall Shale Gas Fracturing Review and Recommendations for Induced Seismic Mitigation*, Department of Energy and Climate Change, London, United Kingdom.

Healy, J., W. Rubey, D. Griggs, and C. Raleigh (1968). The Denver earthquakes, *Science* **161,** no. 3848, 1301–1310.

Herrmann, R. B., S. Park, and C. Wang (1981). The Denver earthquakes of 1967–1968, *Bull. Seismol. Soc. Am.* **71,** no. 3, 731–745.

Holland, A. A. (2013). Earthquakes triggered by hydraulic fracturing in south-central Oklahoma, *Bull. Seismol. Soc. Am.* **103,** no. 3, 1784–1792, doi: 10.1785/0120120109.

Horton, S. (2012). Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake, *Seismol. Res. Lett.* **83,** no. 2, 250–260, doi: 10.1785/gssrl.83.2.250.

Hsieh, P. A., and J. D. Bredehoeft (1981). A reservoir analysis of the Denver earthquakes: A case of induced seismicity, *J. Geophys. Res.* **86,** no. B2, 903–920, doi: 10.1029/JB086iB02p00903.

Hubbert, M., and D. Willis (1957). Mechanics of hydraulic fracturing, *AIME Pet. Trans.* **210,** 153–168, doi: 10.1016/S0376-7361(07)53011-6.

Justinic, A. H., B. Stump, C. Hayward, and C. Frohlich (2013). Analysis of the Cleburne, Texas, earthquake sequence from June 2009 to June 2010, *Bull. Seismol. Soc. Am.* **103,** no. 6, 3083–3093, doi: 10.1785/0120120336.

Kanamori, H., and E. Hauksson (1992). A slow earthquake in the Santa Maria Basin, *Bull. Seismol. Soc. Am.* **82,** no. 5, 2087–2096.

Keranen, K. M., H. M. Savage, G. A. Abers, and E. S. Cochran (2013). Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence, *Geology* 2011–2014, doi: 10.1130/G34045.1.

Keranen, K. M., M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge (2014). Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection, *Science* **345,** no. 6195, 448–451, doi: 10.1126/science.1255802.

Kim, W.-Y. (2013). Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio, *J. Geophys. Res.* **118,** no. 7, 3506–3518, doi: 10.1002/jgrb.50247.

Langenbruch, C., and S. Shapiro (2010). Decay rate of fluid-induced seismicity after termination of reservoir stimulations, *Geophysics* **75,** no. 6, MA53–MA62.

Maxwell, S. (2013). Unintentional seismicity induced by hydraulic fracturing, *CSEG Rec.* **38,** 40–49.
Maxwell, S. C., M. B. Jones, R. L. Parker, W. S. Leaney, M. Mack, D. Dorvall, D. D'Amico, J. Logel, E. Anderson, and K. Hammermaster (2010). Fault activation during hydraulic fracturing, *AAPG Search Discov.* **90172,** 1–4, doi: 10.1190/1.3255145.
McClure, M., and R. Horne (2011). Investigation of injection-induced seismicity using a coupled fluid flow and rate/state friction model, *Geophysics* **76,** no. 6, WC181–WC198, doi: 10.1190/GEO2011-0064.1.
McGarr, A., B. Bekins, N. Burkardt, J. Dewey, P. Earle, W. Ellsworth, S. Ge, S. Hickman, A. Holland, E. Majer, J. Rubinstein, and A. Sheehan (2015). Coping with earthquakes induced by fluid injection, *Science* **347,** no. 6224, 830–831, doi: 10.1126/science.aaa0494.
McGarr, A., D. Simpson, and L. Seeber (2002). 40 Case histories of induced and triggered seismicity, *Int. Geophys.* **81A,** 647–661.
Murray, K. E. (2013). State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, U.S., *Environ. Sci. Technol.* **47,** no. 9, 4918–4925, doi: 10.1021/es4000593.
Nicholson, C., and R. Wesson (1992). Triggered earthquakes and deep well activities, *Pure Appl. Geophys.* **139,** no. 3, 561–578.
Nicholson, C., and R. L. Wesson (1990). Earthquake hazard associated with deep well injection: A report to the U.S. Environmental Protection Agency, *U.S. Geol. Surv. Bull. 1951*, 74 pp.
Petersen, M. D., C. S. Mueller, M. P. Moschetti, S. Hoover, J. L. Rubinstein, A. L. Llenos, A. J. Michael, W. L. Ellsworth, A. F. McGarr, A. A. Holland, and J. G. Anderson (2015). Incorporating induced seismicity in the 2014 United States National Seismic Hazard Model—Results of 2014 Workshop and sensitivity studies, *U.S. Geol. Surv. Open-File Rept. 2015-1070*, doi: 10.3133/ofr20151070.
Raleigh, C. B., J. H. Healy, and J. D. Bredehoeft (1976). An experiment in earthquake control at Rangely, Colorado, *Science* **191,** no. 4233, 1230–1237, doi: 10.1126/science.191.4233.1230.
Rubinstein, J. L., W. L. Ellsworth, A. McGarr, and H. M. Benz (2014). The 2001-present induced earthquake sequence in the Raton Basin of northern New Mexico and southern Colorado, *Bull. Seismol. Soc. Am.* **104,** no. 5, 2162–2181, doi: 10.1785/0120140009.
Shapiro, S. a., and C. Dinske (2009). Fluid-induced seismicity: Pressure diffusion and hydraulic fracturing, *Geophys. Prospect.* **57,** no. 2007, 301–310, doi: 10.1111/j.1365-2478.2008.00770.x.
Skoumal, R. J., M. R. Brudzinski, and B. S. Currie (2015). Earthquakes induced by hydraulic fracturing in Poland Township, Ohio, *Bull. Seismol. Soc. Am.* **105,** no. 1, 189–197, doi: 10.1785/0120140168.
Walsh, F. R. I., and M. D. Zoback (2015). Oklahoma's recent earthquakes and saltwater disposal, *Sci. Adv.* (in press).
Walters, R., M. Zoback, J. Baker, and G. Beroza (2015). Characterizing and responding to seismic risk associated with earthquakes potentially triggered by saltwater disposal and hydraulic fracturing, *Seismol. Res. Lett.* **86,** no. 4, doi: 10.1785/0220150048.
Warpinski, N. R., J. Du, and U. Zimmer (2012). Measurements of hydraulic-fracture-induced seismicity in gas shales, *SPE Hydraul. Fract. Technol. Conf., SPE 151597*, The Woodlands, Texas, 6–8 February 2012, 1–8, doi: 10.2118/151597-PA.
Weingarten, M., S. Ge, J. W. Godt, B. A. Bekins, and J. L. Rubinstein (2015). High-rate injection is associated with the increase in U.S. mid-continent seismicity, *Science* (in press).
Zoback, M. (2012). Managing the seismic risk posed by wastewater disposal, *Earth*, 38–43.

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