On Shaky Ground

FRACKING, ACIDIZING, AND INCREASED EARTHQUAKE RISK IN CALIFORNIA

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MARCH 2014

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Report available at: ShakyGround.org

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Contents

Executive Summary

This report analyzes the earthquake risks associated with an increase in wastewater injection that would result from an expansion of fracking and other unconventional oil production in California's Monterey Shale, including:

- the demonstrated connection between the injection of oil and gas wastewater and induced earthquakes,
- significant gaps in current science and inability of regulators to protect Californians from the dangers associated with these quakes, and
- proximity of many active California wastewater injection wells to active faults and major population centers.

To graphically illustrate the risks, the report includes maps from an online interactive tool developed by the FracTracker Alliance, which show the current extent of oil and gas development, including active wastewater injection wells, fracked and acidized wells, fault lines, and communities.

Key Findings:

1. **A majority of California's active oil and gas wastewater injection wells are close to faults.** Our analysis shows that 54 percent of California's 1,553 active and new wastewater injection wells are within 10 miles of a recently active fault (active in the past 200 years), 23 percent are within 5 miles, and 6 percent are within 1 mile. Because the distance from a wastewater injection well to a fault is a key risk factor influencing whether a well may induce an earthquake, these findings raise significant concerns.

Distance of California's Active/New Wastewater Injection Wells to Recently Active Faults

NUMBER OF ACTIVE/NEW WELLS (PERCENT)	DISTANCE TO RECENTLY ACTIVE FAULT
87 wells (6%)	Within 1 mile
350 wells (23%)	Within 5 miles
834 wells (54%)	Within 10 miles

2. **Millions of Californians live in areas at risk for induced earthquakes.** Some of California's major population centers, such as Los Angeles and Bakersfield, are located in regions where high densities of wastewater injection wells are operating very close to active faults.

3. **Research and monitoring are dangerously inadequate.** No studies to date have evaluated the increased risk of induced earthquakes from California's existing wastewater injection wells. There are fundamental knowledge gaps in understanding the risks of induced seismicity from these wells.
4. **Regulations do not protect Californians from the risk of induced earthquakes.** California has no plan to safeguard its residents from the risks of earthquakes induced by Class II injection wells or oil and gas production. Due to significant knowledge gaps, California's Division of Oil, Gas, and Geothermal Resources (DOGGR) cannot safely regulate the risk of induced seismicity from oil and gas production and wastewater disposal.
5. **Oil industry wastewater disposal poses unacceptable risks**. In light of the known environmental and health risks from drilling, well stimulation and wastewater disposal, the link between wastewater injection wells and earthquakes in other states, the potential for a massive expansion of drilling and wastewater production in the Monterey Shale, and the gaps in scientific knowledge regarding induced seismicity, the best way to protect Californians is to halt hydraulic fracturing, acidizing, and other unconventional oil and gas recovery techniques.

In sum, the findings highlight the lack of assurance that fracking and the injection of oil and gas wastewater can be conducted safely, and demonstrate the need for a halt to fracking, acidizing, and other forms of well stimulation.

This report is necessary because California's oil industry may be on the verge of rapidly expanding unconventional oil production of the Monterey Shale, a vast shale oil deposit in the San Joaquin Valley, parts of the Central Coast, and the Los Angeles basin that underlies many communities, important wildlife habitat, and some of the nation's richest farmland.

Oil and gas production results in billions of gallons of contaminated wastewater that is often disposed of in underground injection wells. In many parts of the eastern and central United States where fracking and wastewater injection have boomed, earthquake activity has increased dramatically. Some regions have experienced a 10-fold increase in earthquake activity. A growing body of research has linked wastewater injection wells to increased earthquake activity, including earthquakes that have damaged homes and infrastructure and caused human injuries. Extracting the oil in the Monterey Shale could produce almost 9 trillion gallons of wastewater.

California is uniquely vulnerable to seismic events, with more citizens and infrastructure at risk from earthquakes than any other U.S. state. Seven of the ten U.S. metropolitan areas with the highest estimated annualized losses from earthquake damage are located in the Golden State. An increase in damaging seismic activity would be devastating to California and its economy.

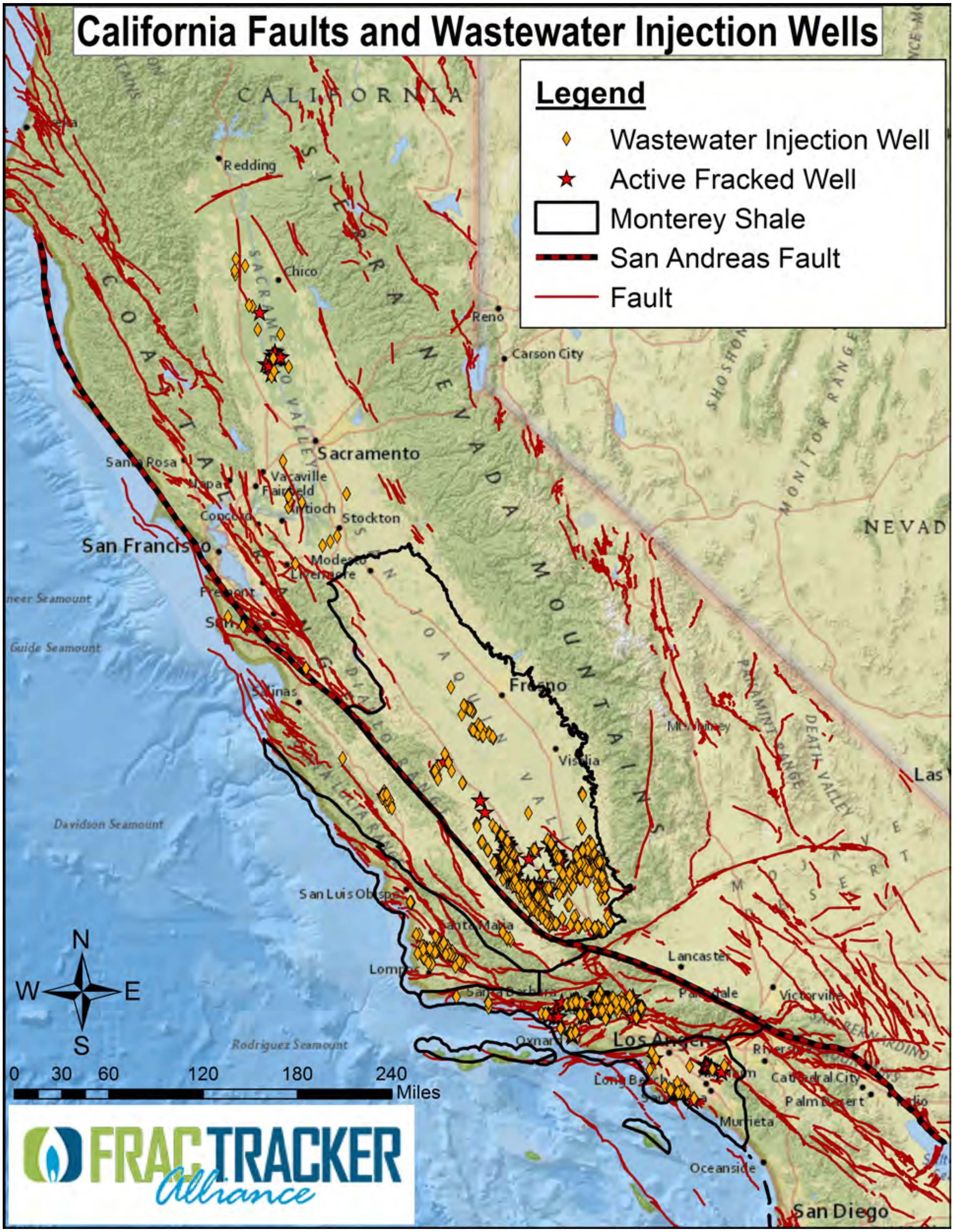


FIGURE 1: California's Faults and Wastewater Injection Wells

Fracking, Wastewater Injection Wells, and Increased Earthquake Risks

1. Fracking and acidizing produce large volumes of contaminated wastewater.

The development of unconventional oil and gas recovery techniques, such as hydraulic fracturing and acidizing, has allowed for a rapid expansion of shale oil and gas development across many parts of the United States. Hydraulic fracturing, or fracking, is a well stimulation technique that releases oil and gas from relatively impermeable formations, such as shale and tight sands, allowing for the extraction of previously unreachable hydrocarbons. Fracking typically involves pumping high volumes of water, sand, and chemicals at high pressures into the rock formation, causing it to crack and release oil and gas.[1]

Although fracking has been done in the U.S. for many years, recent developments, such as directional and horizontal drilling and new chemical fluid mixtures, have facilitated an increase of drilling in previously uneconomic geologic formations.

Acidizing, another well stimulation technique, involves the injection of hydrochloric and/or hydrofluoric acids, along with some of the same fluids used for fracking.[2] These chemicals modify the permeability of a geologic formation, allowing increased hydrocarbon flow. In California, acidizing may be the well stimulation treatment of choice for the oil and gas industry to access the Monterey Shale, due to the highly fractured geology of the state.[3]

Hydraulic fracturing, acidizing and other unconventional well stimulation methods create large quantities of wastewater — called flowback and produced water — that contain contaminants which can reach toxic concentrations. Flowback is the fluid that returns to the surface after fracturing or acidizing is completed, but before oil and gas is recovered from the well. Produced water is primarily composed of the formation fluid that comes to the surface once production of oil and gas has begun. Produced water is associated with all forms of oil and gas production, regardless of the well stimulation technique.

Both flowback and produced water can contain chemicals from the fracking fluid and the fluids rising from deep in the rock formation, which can be harmful to human health. An estimated 15 to 100 percent of fracking fluids return to the surface as wastewater.[4] More than 75 percent of the chemical additives in fracking fluids can affect important organs, and 25 percent can cause cancer.[5] Flowback and produced water are typically very saline and can contain heavy metals such as lead, organic contaminants such as benzene and toluene, and naturally occurring radioactive materials from deep in the formation,[6] which makes treatment and recycling difficult.

Recent estimates report that flowback volumes can range between 420,000 gallons to more than 2.5 million gallons per fracking event, depending on the characteristics of the formation, the amount of fluid injected, and the type of hydrocarbon being extracted.[7] Produced water can reach millions of gallons over the lifetime of the well.[8] In California, oil and gas wells averaged approximately 2.3 million gallons of wastewater per well in 2011.[9]

2. Underground injection wells are the most common method for disposing of oil and gas wastewater in California and many other parts of the U.S.

The wastewater produced during oil and gas extraction is either disposed of or reused for additional oil and gas extraction in a process called "secondary recovery" or "enhanced oil recovery (EOR)." In California and many other parts of the country, the most common wastewater disposal method is trucking or piping the wastewater for injection into deep wastewater injection wells, drilled into porous rock thousands of feet underground.[10] These wastewater injection wells are categorized as Class II Underground Injection Wells by the U.S. Environmental Protection Agency (EPA), which oversees their regulation under the Safe Drinking Water Act's (SDWA) Underground Injection Control (UIC) Program.[11] In California, the Division of Oil Gas and Geothermal Resources (DOGGR) received primacy to directly regulate the state's Class II underground injection wells in 1982.[12]

There are about 30,000 Class II wastewater injection wells in operation in the U.S. that are used for wastewater disposal from oil and gas production.[13] Texas leads the nation with about 7,500 active wastewater injection wells,[14] followed by Oklahoma with an estimated 4,400 active wells.[15]

California has an estimated 2,583 wastewater injection wells, of which 1,553 are currently active.[16] Wastewater injection wells are located throughout the state, from the Chico area in northern California, to Kern County in the Southern San Joaquin Valley, to Los Angeles in the south, and even offshore near Santa Barbara.[17]

California's oil and gas fields produce billions of gallons of contaminated wastewater each year that must be managed — about 15 times more wastewater than oil.[18] In 2012 alone, California's oil and gas industry produced an estimated 124 billion gallons of wastewater.[19] Much of this wastewater is permanently disposed of in wastewater injection wells. According to the most recent data available from the U.S. Department of Energy, in 2007 California's oil and gas industry disposed of 22 percent of the wastewater it produced into injection wells, totaling more than 23 billion gallons[20] — equivalent to about 35,500 Olympic-sized swimming pools. About 69 percent of the wastewater was reused for enhanced recovery,[21] and small amounts are disposed of in unlined percolation ponds, lined evaporation ponds, sewer systems, and surface waters.[22]

In 2012 alone, California's oil and gas industry produced an estimated 124 billion gallons of wastewater.

The amount of wastewater being disposed of in injection wells has skyrocketed in states where fracking has proliferated in recent years.

In Texas, for example, the amount of wastewater injected into disposal wells increased from 1.9 billion gallons in 2005 to nearly 147 billion gallons in 2011 — a 76-fold increase.[23]

California's oil and gas industry may be on the verge of rapidly expanding unconventional oil production in the Monterey Shale, a vast shale deposit in the San Joaquin Valley, parts of the Central Coast and the Los Angeles basin, which holds an estimated 13.7 billion barrels of technically recoverable shale oil.[24] If the oil and gas industry develops the Monterey Shale, the production of wastewater and demand for wastewater injection wells are likely to increase substantially. For example, based on the historically reported ratio of 15 times more wastewater than oil produced in California, extracting the Monterey Shale's estimated 13.7 billion barrels of recoverable oil could produce 8.6 trillion gallons (205.5 billion barrels) of wastewater — enough to fill almost 13 million Olympic-sized swimming pools.

3. Scientists have long documented that wastewater injection wells can induce earthquakes.

The underground injection of wastewater has long been documented to induce earthquakes. Wastewater injected into rock formations can build up significant pressure depending on the volume of wastewater, rate of injection, and the permeability of the rock. This pressure build-up can induce an earthquake if the pressure is relayed to a fault that is already stressed and close to failure. The pressure can reduce the natural friction on the fault enough to cause it to slip and trigger an earthquake.[25] The larger the fault, the larger the magnitude of earthquakes it can host.[26]

As early as the 1960s, scientists began documenting seismic activity from the injection of large volumes of fluids underground.[27] One of the first recorded cases of human-induced earthquakes due to underground fluid injection occurred in 1961, when the U.S. Army began disposing of millions of gallons of liquid hazardous waste 12,000 feet below the surface at the Rocky Mountain Arsenal near Denver, Colorado. This injection spurred more than 1,500 earthquakes over a five-year period in an area not known for active seismicity. It culminated in three earthquakes of magnitudes 5.0 to 5.5 more than a year after injection ceased, the largest of which caused more than $500,000 in damages. Geologists discovered that the Army well had been drilled into an unknown fault. This example, as well as two other well-studied fluid injection projects — at Rangely, Colorado, in the 1970s and Paradox Valley, Colorado, in the 1990s — established that wastewater injection wells could induce earthquakes large enough to cause significant damage.[28]

4. Wastewater injection wells have induced felt and damaging earthquakes of magnitudes 4 and 5 in regions where fracking has proliferated.

In many areas of the U.S. where fracking has proliferated, earthquake activity has increased dramatically. As scientists begin to investigate the causes of these earthquake swarms, a growing number of studies have attributed some of this increased earthquake activity, and some of the largest earthquakes, to the underground injection of oil and gas wastewater in these regions.[29]

Within the Midwestern and Eastern U.S., the number of recorded earthquakes began to increase in 2003, rising dramatically after 2009.[30] In total, an average of 100 earthquakes per year of magnitude[31] 3 (M3) or larger struck between 2010 and 2012, compared with only 21 per year between 1967 and 2000.[32] States experiencing elevated levels of earthquake activity in parallel with booms in unconventional oil and gas development include Oklahoma, Texas, Colorado, New Mexico, Arkansas, Ohio, and West Virginia.[33]

Earthquake activity has increased dramatically in many areas of the U.S. where fracking has proliferated.

Earthquakes of M3 to M5 have been scientifically linked to wastewater injection wells in at least six states: Oklahoma, Texas, Colorado, New Mexico, Arkansas, and Ohio. The largest of these was a M5.7 earthquake near Prague, Oklahoma, outside of Oklahoma City which was the biggest in the state's history. It destroyed 14 homes, damaged infrastructure and numerous buildings, and injured two people.[34]

Other large earthquakes attributed to wastewater injection include a M4.8 in Texas, M5.3 in Colorado, M4.7 in Arkansas, and M3.9 in Ohio, as summarized by state below:

Oklahoma: Oklahoma's earthquake activity has increased dramatically since 2009, with the increase linked to wastewater injection wells.[35] The state has been hit by more than 200 earthquakes of M3 or larger since 2009 — about 40 per year — compared to 1 to 3 a year between 1975 and 2008.[36] According to the U.S. Geological Survey (USGS), the likelihood of an earthquake in central Oklahoma has increased by a factor of 10.[37] These earthquake swarms are striking in populated areas, culminating with the largest earthquake ever recorded in the state — the damaging M5.7 earthquake near Prague outside Oklahoma City in 2011, which scientists have linked to injection wells.[38] In October 2013, the USGS and Oklahoma Geological Survey (OGS) warned that the "earthquake swarm" around Prague and Oklahoma City has increased hazards for city and rural residents, and stated that wastewater injection wells may be a "contributing factor."[39] This warning caused the State Insurance Commissioner to recommend that Oklahoma residents buy earthquake insurance.[40] Recent earthquake swarms have also hit near Marietta in southern Oklahoma and Enid to the north, with these swarms also thought to be linked to wastewater injection wells.[41]

Texas: Several regions of Texas have experienced increased earthquake activity near wastewater injection wells in areas where no previous seismic activity has been recorded. In regions near Dallas-Ft. Worth, Cleburne, and Timpson, scientists have linked increased earthquake activity to wastewater injection wells.[42] Timpson, Texas, has been struck by a series of damaging earthquakes, including the largest ever recorded in eastern Texas — a M4.8 in May 2012 which caused significant structural damage[43] — and M4.1 and M4.3 earthquakes in 2013.[44] In the heavily populated Dallas-Fort Worth region, scientists have attributed a series of small earthquakes in 2009 to wastewater injection.[45] Since 2009, the region has been hit by stronger earthquakes between M3 and M4.[46]

Colorado/New Mexico: Earthquake activity has increased dramatically in the Raton Basin of southern Colorado and northern New Mexico, culminating in a M5.3 earthquake near Trinidad, Colorado, in August 2011, with increased seismicity being attributed to wastewater injection wells.[47] The number of earthquakes of M3 or greater increased from 0.16 per year in the 31-year period before injection, to 9.5 per year after injection began in 2001.

Arkansas: Earthquake activity in central Arkansas increased sharply in 2010 and 2011, when earthquake swarms hit near the towns of Guy and Greenbrier, close to injection wells, culminating in a M4.7 earthquake in February 2011.[48] After the first wastewater disposal well became operational in April 2009, the rate of M≥2.5 earthquakes skyrocketed, with one in 2007, two in 2008, 10 in 2009, 54 in 2010, and 157 in 2011. Scientists have determined that these swarms were likely induced by wastewater injection.[49]

Ohio: The injection of wastewater into a deep well has been linked to a series of earthquakes in a previously earthquake-free region near Youngstown, Ohio.[50] More than 109 earthquakes occurred between January 2011 and February 2012, with a M3.9 earthquake striking on December 31, 2011.

This growing body of research demonstrates that injecting wastewater into underground disposal wells can induce earthquakes. These studies also illustrate what is currently known and unknown about the risks of induced earthquakes from wastewater injection wells, including key uncertainties. Some important facts and uncertainties include:

- While injection wells can operate for years without creating felt earthquakes, some wastewater injection wells have induced earthquakes that can cause structural damage and human injuries, and the number of documented cases is growing.
- While induced seismicity often occurs within months of injection, the onset can be delayed for many years — as much as 20 years in some instances — after the initiation of injection.[51]
- Induced seismicity, including large earthquakes, may continue for months to years after injection is stopped.

- While many induced earthquakes originate near the injection point, they have also occurred up to 7.5 miles (12 kilometers) away, indicating that the potential influence of wastewater injection wells can extend out many miles.[52] Research has not established a maximum distance over which injection wells can induce earthquakes.
- The maximum possible magnitude of an induced earthquake that can be triggered by injection is unknown.

5. Hydraulic fracturing has induced felt earthquakes of magnitudes 2 and 3.

Fracking appears to pose a lower risk of inducing destructive earthquakes than the injection of oil and gas wastewater. Fracking intentionally cracks the shale rock around wells to release oil and gas deposits and routinely produces small earthquakes (M<1) typically not felt at the surface.[53] However, several recent studies have reported that fracking has induced earthquakes of magnitudes 2 and 3 in Oklahoma, British Columbia, and the United Kingdom,[54] including a M3.8 event.

These cases illustrate that fracking can induce larger magnitude earthquakes when the rock formation being fracked intersects a fault:

Oklahoma: In January 2011, a series of 116 earthquakes, ranging from M0.6 to M2.9, occurred near a well being hydraulically fractured in south-central Oklahoma. Multiple earthquakes were felt by a local resident. A study by a scientist at the OGS found that the area was highly faulted, and concluded that "it is likely that hydraulic fracturing triggered the earthquakes observed in this study."[55]

British Columbia: A 2012 study by the British Columbia Oil and Gas Commission determined that seismic events reported in the Horn River Basin between April 2009 and December 2011 were caused when fracking fluids were injected into a fault.[56] A series of 38 earthquakes were recorded between M2.2 and M3.8, with the largest earthquake felt by workers.

United Kingdom: A series of earthquakes culminating in a M2.3 near Blackpool, England, in 2011 has been attributed to fracking.[57]

6. Earthquakes may cause oil and gas leaks and spills, and pose a risk to groundwater near oil and gas infrastructure.

There is ample cause for concern about the potential harm to groundwater associated with earthquakes near oil and gas wells. All wells, including production and wastewater injection wells, rely on the integrity of the well casing to prevent contamination of underground aquifers. Seismic activity that occurs close to wells may increase the likelihood of damaging the well casing or cementing, which can allow contamination of underground sources of drinking and irrigation water from the migration of hydrocarbons, well stimulation and drilling chemicals, or produced water.

Well casing failures are common, but the extent to which they are caused by or exacerbated by seismic movement is unknown. In Pennsylvania, a study using data supplied by industry found failure rates of 6 to 9 percent.[58] A ProPublica review of injection wells nationwide found that from 2007 to 2010, more than 7,000 (3 percent) of 220,000 wells showed signs of leakage, and more than 17,000 (8 percent) had received violations.[59] The same report found that in California over that time period there were 12 cases of groundwater contamination and 63 cases of significant leaks from injection wells.[60]

California lacks key data on well casing failures. DOGGR does not maintain a database of well casing failures, and the agency is unable to identify which wells have failed and the rate at which wells experience integrity failures. The unknown extent of well casing failures and the lack of understanding of the impacts of seismic activity on well casing integrity are especially troubling for California. The state's elevated risk of seismic activity, combined with additional induced seismicity risk from well stimulation and underground injection, could lead to disastrous consequences should an earthquake cause major well casing failures. The rate of well casing failure, along with the effects of seismic activity on well integrity, should be further analyzed to better understand the risk of groundwater contamination from oil and gas wells in California.

Although there is no comprehensive analysis, evidence of well casing failures linked to earthquakes already exists in the state. For example, in Ojai, California, API well #11101020 experienced a failure directly after an earthquake occurred on the nearby San Cayetano fault. According to DOGGR, on March 3, 2006, the Ojai 36 well, located in the Sespe oil field, 1.23 miles from the San Cayetano fault (Figure 2), was plugged and abandoned after a M3.1 earthquake triggered a 5 barrel-per-minute leak of produced water.[61] The well log indicates that there is no record of when the well was initially drilled, but it was deepened in 1918. Like many existing oil and gas wells which were drilled decades ago, there is no record of any assessment of nearby faults and seismic threats to well casings.[62]

In Ojai, California, API well #11101020 experienced a failure directly after an earthquake occurred on the nearby San Cayetano fault.

The example of Ojai 36 demonstrates how seismic events may cause well casing failure and that drilling in seismically active areas may pose increased risk of failures and potential groundwater contamination.

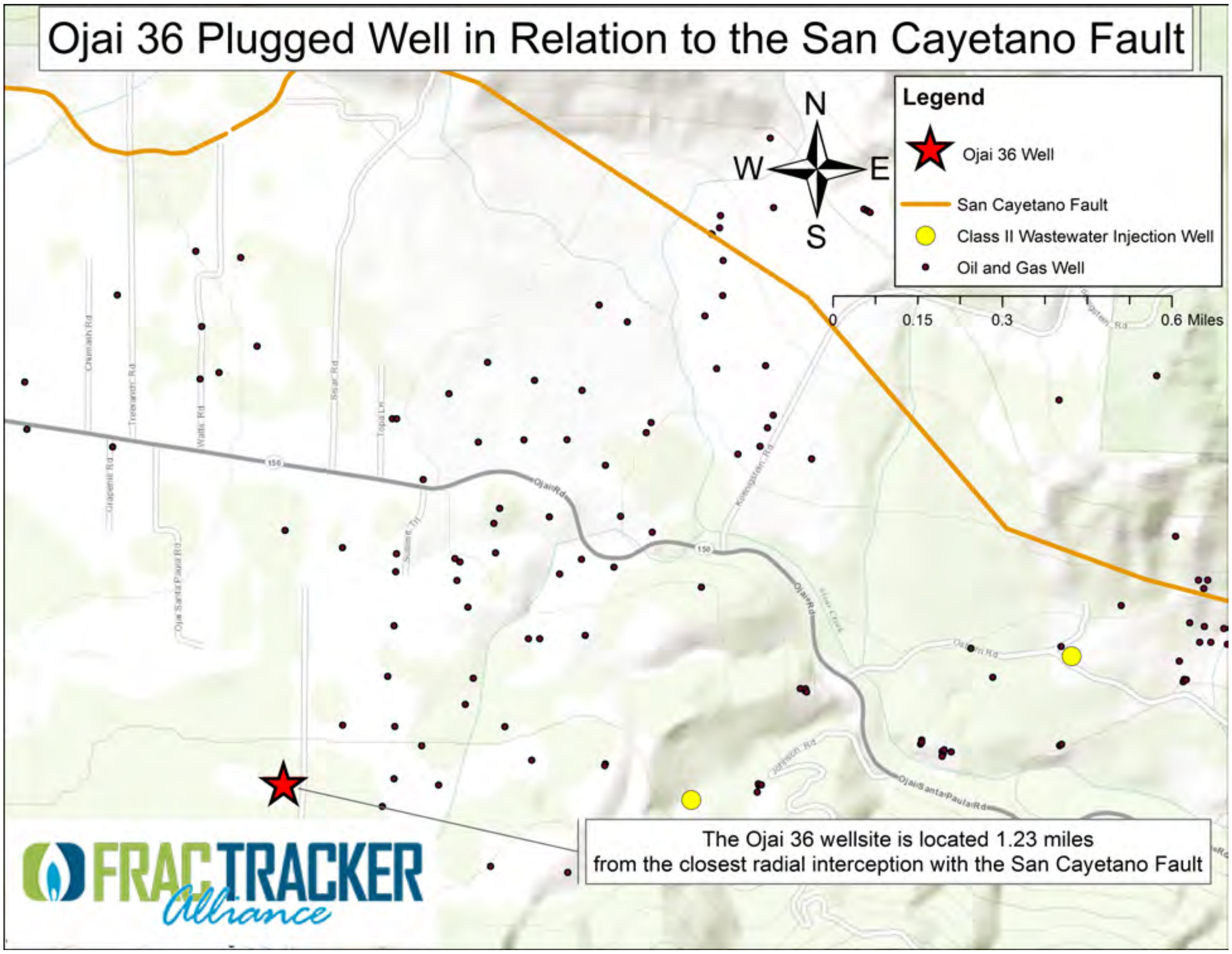


FIGURE 2: Location of Well Failure in Ojai, CA, In Relation to the San Cayetano Fault.

Evaluating Earthquake Risk from Wastewater Injection Wells and Fracking in California

1. California is one of the most seismically active states in the nation, with many active faults and more citizens and infrastructure at risk from earthquakes than any other state.

California lies within the planet's Ring of Fire, a seismically active region surrounding the Pacific Ocean from New Zealand, to Alaska, to Chile. Ninety percent of the world's earthquakes and 81 percent of the largest earthquakes occur along the Ring of Fire.[63] In California, there are thousands of small earthquakes per year that are attributed to the complex system of faults that crisscross the state. The most prominent is the San Andreas fault which cuts across California, forming the boundary between the Pacific and North American tectonic plates.[64] Other active faults are the San Jacinto fault in Southern California and the Mendocino Triple Junction in Northern California, which have historically produced large earthquakes.[65]

Due to its frequent seismic activity and large population centers, California has more citizens and infrastructure at risk from earthquakes than any other U.S. state.[66] In fact, seven of the 10 U.S. metropolitan areas with the highest estimated annualized losses from earthquake damage are in California, with the Los Angeles-Long Beach-Santa Ana area ranking first.[67]

The San Andreas fault and the Hayward-Rodgers Creek fault have the greatest probability of generating a large earthquake.[68] Many earthquakes typically occur within 31 miles (50 kilometers) of the San Andreas fault, including many with M7.0 or above. Examples include the 1906 San Francisco earthquake (M7.9) and the 1989 Loma Prieta earthquake (M7.0). A number of moderate to large earthquakes — M5.5 or above — have occurred in faults away from the San Andreas. These include the 1952 Kern County earthquake (M7.5), the 1971 San Fernando earthquake (M6.7), and the 1994 Northridge earthquake (M6.7).

In California, earthquakes pose added risks from landslides and liquefaction, particularly along the densely populated coast. Liquefaction, a type of ground failure specific to earthquakes, occurs when water-saturated sand and silt behave like a liquid due to the trembling of the earth. The soils can then no longer support structures, may flow down even gentle slopes, and erupt to the surface as sand boils. Liquefaction usually leads to settlement of the surface in uneven patterns that damage infrastructure such as buildings, roads, and pipelines.[69] Areas with high liquefaction hazards include landfills, particularly those in areas once submerged by water, as well as wetlands, river floodplains, and stream channels.[70] Areas of particular concern for liquefaction include the margins of San Francisco Bay[71] and parts of Los Angeles County (Figure 3).

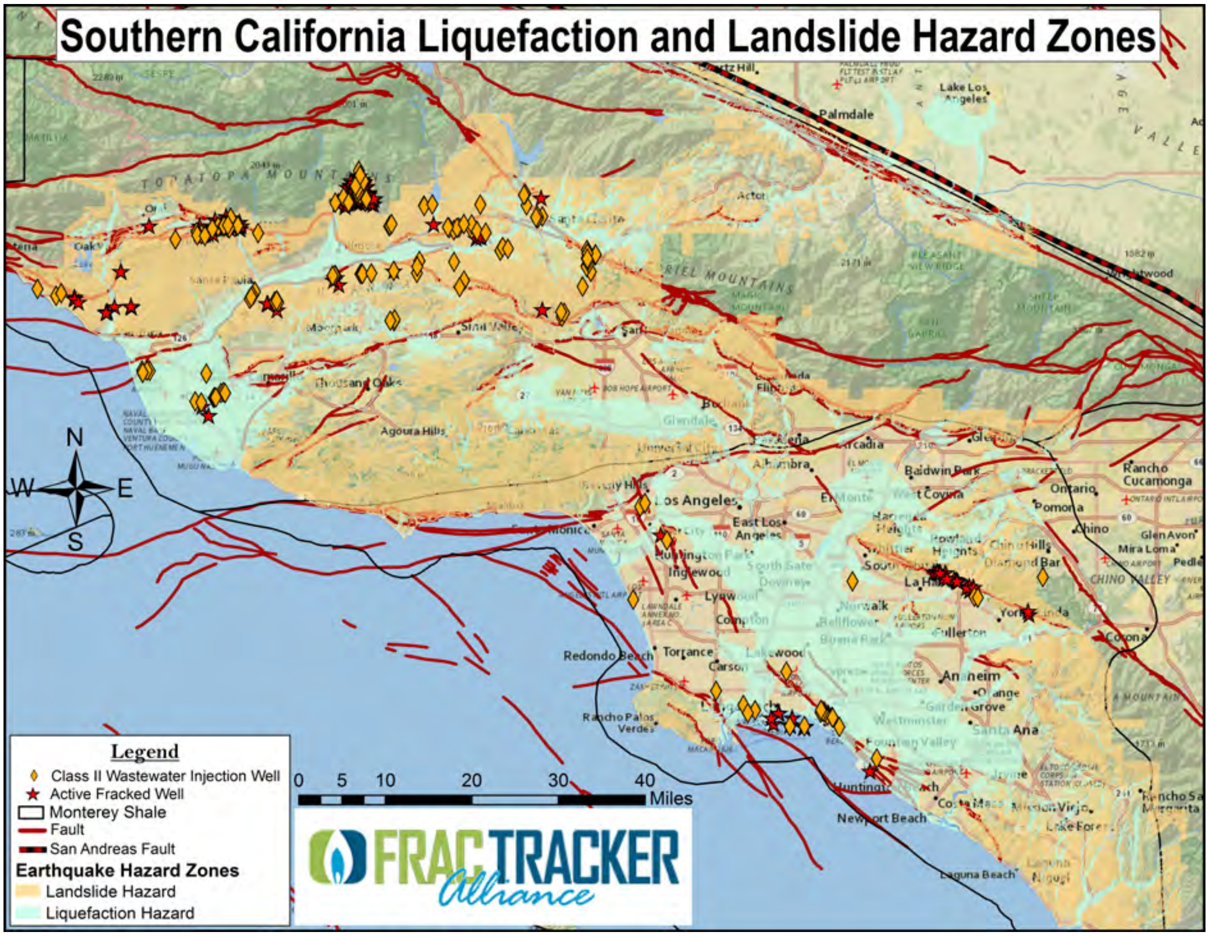


FIGURE 3. **Landslide and Liquefaction Zones in Southern CA with Class II Wastewater Injection Wells and Fracked Wells. Areas with high liquefaction hazards include landfills, particularly those in areas once submerged by water, as well as wetlands, river floodplains, and stream channels. Areas of particular concern for liquefaction include the margins of San Francisco Bay and parts of Los Angeles County.**

2. More than half of California’s 1,553 active wastewater injection wells are within 10 miles of a recently active fault.

Two interactive maps developed by the FracTracker Alliance show the current extent of oil and gas development, seismic activity, and seismic hazards throughout California. The maps depict the state’s fault lines, wastewater injection wells, fracked and acidized wells, liquefaction and landslide hazard zones, and the Monterey Shale that is the focus for unconventional development. Users may zoom in and out to determine if their neighborhood is affected by oil and gas development and wastewater injection wells, or lies in a seismic hazard zone. Links are provided here: California Geological Hazards Map, Injection Wells and Hydraulic Fracturing in California’s Fault Zones. In the maps, the fault history is categorized into four groups based on the last time that each fault was active: Historic (fault experienced earthquake activity in the last 150 to 200 years), Holocene (activity in the last 11,000 years), Late Quaternary (activity in the last 750,000 years), and Quaternary (activity in the last 1,600,000 years), using the definitions from the USGS and the California Geological Survey (CGS). Detailed descriptions of the maps are provided in Appendix A.

Based on this data, we analyzed the proximity of California’s active and new Class II wastewater injection wells to faults in order to assess the risks that injection wells may pose to Californians. We evaluated recently active (“Historic”) faults — defined as those with activity in the past 150 to 200 years — and Quaternary faults — defined as those with activity in the past 1.6 million years — using data from the CGS[72] and USGS.[73] We also analyzed a subset of “high-magnitude faults” identified as causing earthquakes greater than M6. New wells are those that have been permitted, may have been drilled, but are not yet actively disposing fluids by injection. A detailed methodology is presented in Appendix A. The distances of both active and inactive wastewater injection wells to faults is presented in Appendix B.

Our analysis shows that more than half of California’s 1,553 active and new Class II wastewater injection wells are within 10 miles of a recently active fault that has caused an earthquake in the past 200 years. Specifically, 834 wells (54 percent) are within 10 miles of a recently active fault, 350 wells (23 percent) are within 5 miles, and 87 wells (6 percent) are within 1 mile (Table 1). Of added concern, 42 wells are within 10 miles of a recently active, high-magnitude fault that has caused an earthquake greater than M6 in the past 150 years, 30 wells are within 5 miles, and one well is within 1 mile.

More than half of California’s 1,553 active and new wastewater injection wells are within 10 miles of a recently active fault and almost one-quarter are within 5 miles.

When all faults are considered, our analysis found that 1,197 active and new wastewater injection wells (77 percent) are within 10 miles of a Quaternary fault, 808 wells (52 percent) are within 5 miles, and 302 wells (19 percent) are within 1 mile (Table 2). Of these, 529 wells are within 10 miles of a high-magnitude Quaternary fault that has caused an earthquake greater than M6 in the past 1.6 million years, 249 wells are within 5 miles, and 53 wells are within 1 mile.

The close proximity of California's wastewater injection wells to faults raises significant cause for concern over the potential for these wells to induce earthquakes. Earthquakes have been induced at distances up to 7.5 miles (12 kilometers) from an injection well,[74] and many of California's active wastewater injection wells are located much closer to faults. Scientists have recommended using 12.4 miles (20 kilometers) as the distance of concern for evaluating whether an injection well might induce an earthquake,[75] and the vast majority of California's active and new injection wells lie within this distance.

TABLE 1. Number of active and new wastewater injection wells within 1, 5, and 10 miles of recently active faults that have caused earthquakes in the past 200 years

NUMBER OF ACTIVE/NEW WELLS (PERCENT)	DISTANCE TO FAULT
87 wells (6%)	Within 1 mile
350 wells (23%)	Within 5 miles
834 wells (54%)	Within 10 miles

TABLE 2. Number of active and new wastewater injection wells within 1, 5, and 10 miles of Quaternary faults that have caused earthquakes in the past 1.6 million years

NUMBER OF ACTIVE/NEW WELLS (PERCENT)	DISTANCE TO FAULT
302 wells (19%)	Within 1 mile
808 wells (52%)	Within 5 miles
1,197 wells (77%)	Within 10 miles

We also found that some of the state's major population centers, such as Los Angeles and Bakersfield, are in regions where high densities of wastewater injection wells are located near recently active faults (Figure 4). The impacts of induced earthquakes can be particularly costly in these heavily populated regions.

Some of the state's major population centers such as Los Angeles and Bakersfield are in regions where high densities of wastewater injection wells are near recently active faults.

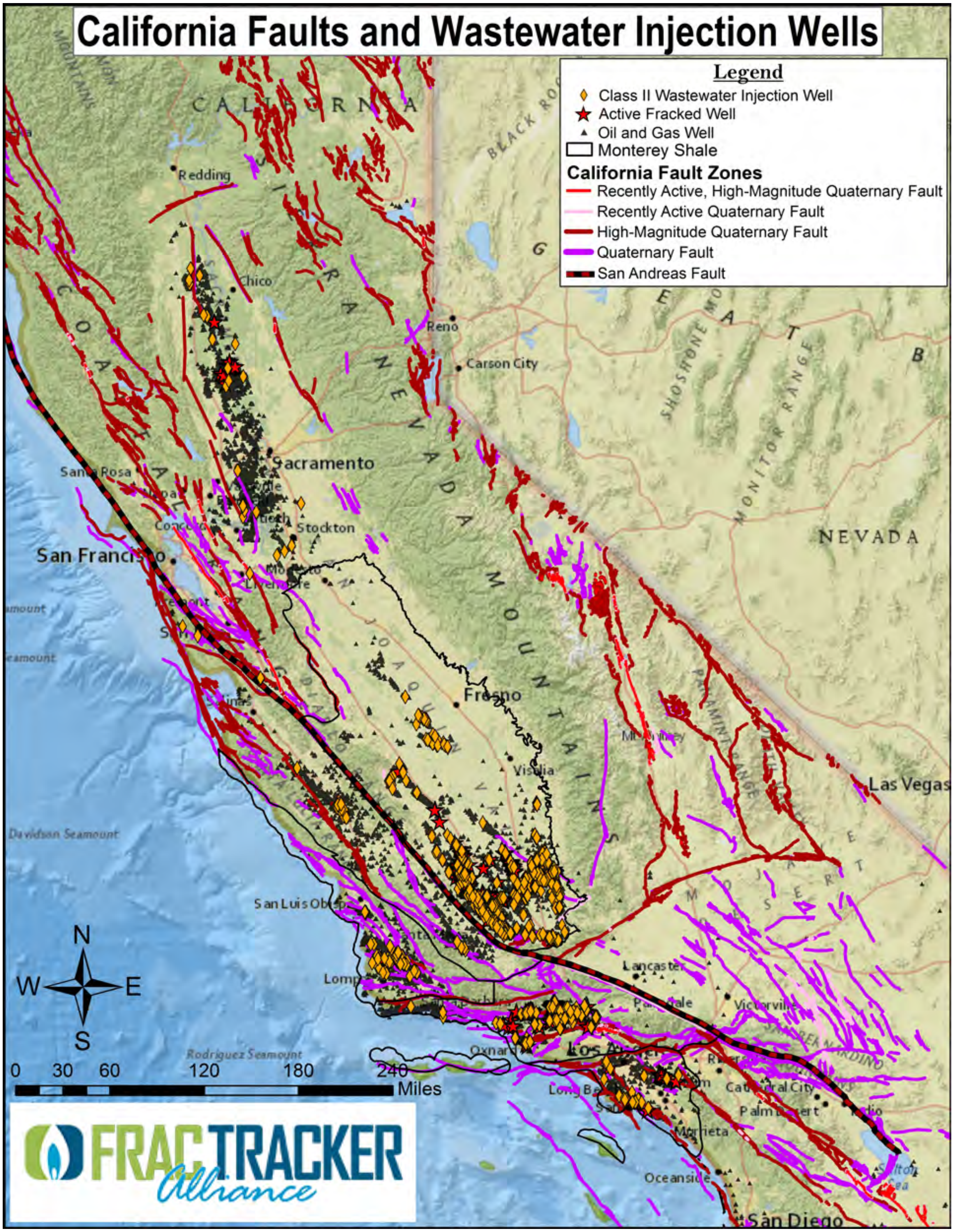


FIGURE 4. California Faults with Class II Wastewater Injection Wells and Fracked Wells. High densities of wastewater injection wells are located near recently active faults.

We highlight three at-risk regions — Kern County, Ventura County, and Los Angeles County:

Kern County: Just to the west of Kern County lies the San Andreas fault — one of the most active faults in the world. Just a few miles from the fault, a large concentration of underground injection wells litters the landscape (Figure 5). There are additional injection wells throughout the county, as well as hundreds of oil wells that are actively fracked and acidized. In 1952, a M7.5 earthquake struck the city of Bakersfield, causing millions of dollars in damage. Kern County produces nearly 80 percent of all oil in California. An earthquake in the area could cause significant environmental damage from well ruptures and spills, as well as injuries, loss of life, and monetary damages.

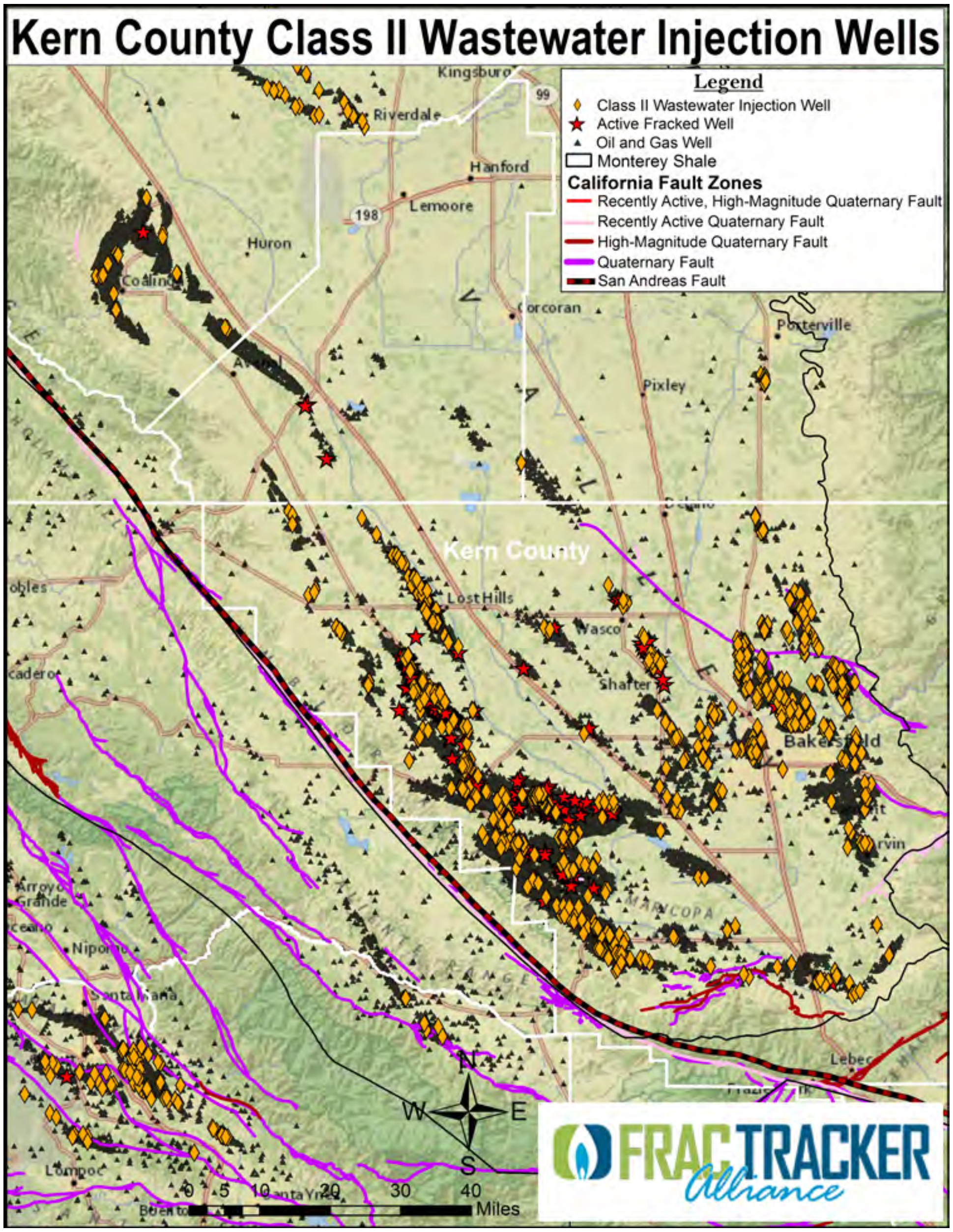


FIGURE 5. **Kern County Faults with Class II Wastewater Injection Wells and Fracked Wells**

Ventura County: Wastewater injection and oil production, including fracking and acidizing, is occurring near faults in the mountains north of the cities of Ventura and Oxnard (Figure 6). These regions are also high-hazard areas for liquefaction and landslides. Should a significant earthquake occur, it would put hundreds of thousands of residents in danger and could cause billions of dollars in infrastructure damage. The CGS estimated a loss of nearly $82 million in the Ventura-Oxnard area in 2010 due to seismic activity.[76] Ventura County lies in the southern edge of the Monterey Shale, one of the areas of most interest for future oil and gas development in the state.

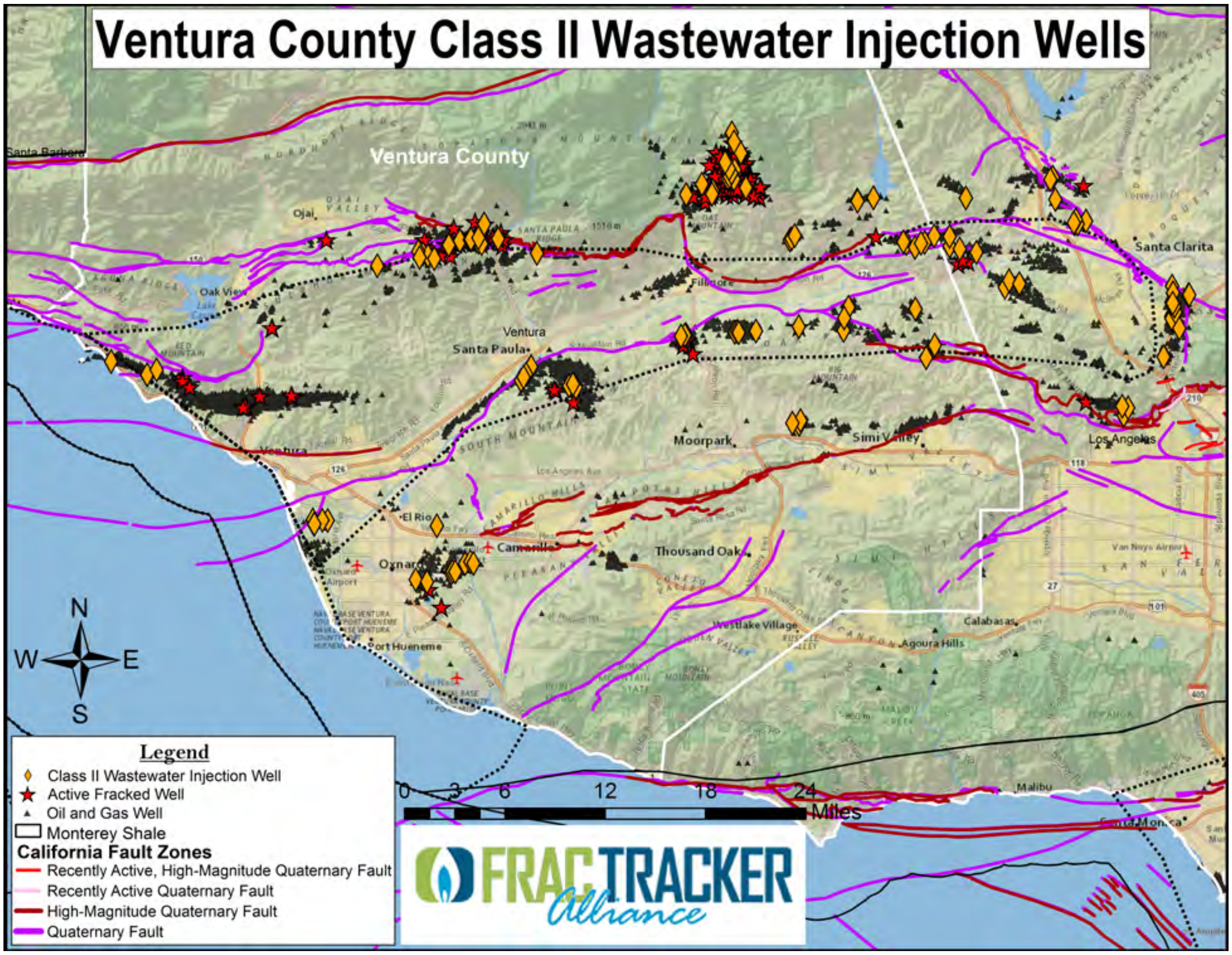


FIGURE 6. **Ventura County Faults with Class II Wastewater Injection Wells and Fracked Wells**

Los Angeles County: One of the main areas of concern lies in Los Angeles County where underground injection wells and oil and gas wells subjected to hydraulic fracturing and acidizing are located very near faults that have been shown to be active in the past 150 to 200 years (Figure 7).

The Inglewood oil field, which lies just southwest of downtown Los Angeles and north of the Long Beach area, is littered with disposal wells that receive millions of gallons of wastewater every year. Estimates by the CGS showed a loss of nearly $1.1 billion for the Long Beach/Los Angeles area from seismic activity in 2010 alone.[77]

Were a major earthquake to occur, it could devastate the county. For example, the "ShakeOut Scenario" from the USGS and CGS estimated that a nearby M7.8 earthquake along the San Andreas fault could cause 1,800 fatalities and nearly $213 billion in economic damages.[78] Additionally, much of Los Angeles County lies in high-hazard areas for liquefaction and landslides.

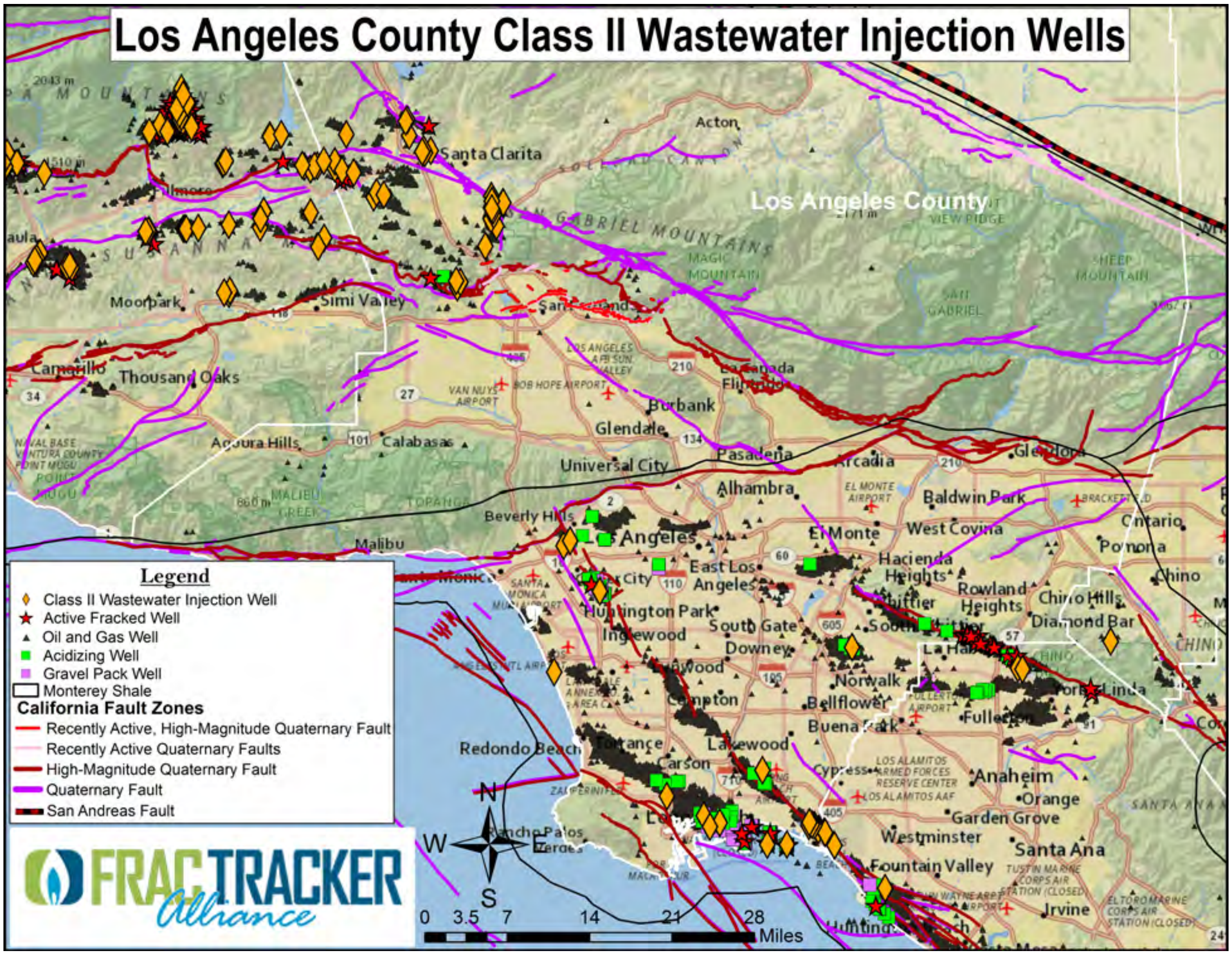


FIGURE 7. LA County Faults with Class II Wastewater Injection Wells and Fracked Wells

3. Critical gaps in monitoring and information prevent the effective detection and risk assessment of human-induced earthquakes.

Despite the advances in research linking wastewater injection wells to induced earthquakes in the Eastern and Midwestern U.S., very little research and monitoring of the earthquake risks from wastewater injection has been conducted in California, despite the state's long history with active faults. At present, no studies have evaluated the potential increase in earthquake risks from the several thousand existing wastewater injection wells, and fracked and acidized wells, in the state. In short, we simply do not know the extent to which existing oil and gas wells and wastewater injection wells in California may have already induced earthquakes.

Other fundamental questions related to the risks of induced seismicity from wastewater injection wells remain unanswered. Several key knowledge gaps exist:

- What is the largest earthquake that could be induced by wastewater injection and fracking activities?
- What is the maximum distance from a fault over which an injection well can induce an earthquake? Examples to date indicate that earthquakes have been induced up to 7.5 miles (12 kilometers) from an injection well.
- What is the time period following the initiation of injection over which earthquakes can be induced, since induced seismicity often occurs within months of initiation but can also occur after many years?
- How quickly can induced seismicity be "turned off" after stopping injection activities, since studies indicate that there may be delays of months or in some cases more than a year?
- How does the density of wells in an area affect the risk of inducing an earthquake? Does a greater density of wells increase this risk?
- What is the risk that wastewater injection wells and oil and gas production wells (including those that have been stimulated), including plugged and abandoned wells, could be damaged by earthquake activity so that they contaminate drinking water sources?
- When and why will a particular injection well induce an earthquake? Why do some injection wells induce earthquakes while others in the same region do not?

Unfortunately, much of the information needed to assess earthquake risks from wastewater injection and oil and gas production wells in California is lacking or incomplete because of (1) the state's failure to require the oil and gas industry to submit critical fluid injection data, (2) gaps in the state's earthquake monitoring networks, and (3) the limitations on collecting comprehensive information on faults and geology.

California regulations have two primary requirements related to fluid injection data from wastewater injection wells: (1) the permit for an injection well must include an injection plan with an estimate of the maximum-anticipated surface injection pressure and daily rate of injection, and an analysis of the injection liquid,[79] and (2) "data shall be maintained to show performance of the project and to establish that no damage to life, health, property, or natural resources is occurring by reason of the project."[80] At present, California only requires industry to submit coarse-scale monthly injection volumes and wellhead pressures,[81] which makes it difficult to determine whether a particular wastewater injection well may have induced an earthquake.

The quantity and distribution of seismic monitoring stations are critical for accurately characterizing the seismicity of a region and determining whether an earthquake is natural or induced. In California, monitoring and reporting of earthquake activity is coordinated under the California Integrated Seismic Network (CISN), a public and private network of monitoring stations.[82]

According to the CISN, the number, type, and distribution of seismic stations are sparse in many parts of the state, and considered inadequate for "producing the best quality of earthquake information from all parts of the state."[83] Collecting data on smaller magnitude earthquakes between magnitudes 1.5 and 2 is particularly important since these smaller earthquakes are much more common than larger ones, can provide warnings that larger magnitude earthquakes are coming, and allow for the statistically robust detection of induced earthquakes.

Critical information on faults and geology is also lacking. California's fault maps are not complete. Some potentially destructive fault types, such as strike-slip faults and blind thrust faults, can be difficult to detect even with traditional seismic imaging technology.[84] Modern 3-D seismic imaging technology that allows for better fault detection is very costly, making it unlikely to be commonly used. There are technological limitations on collecting information on the geological characteristics related to induced seismicity, including pore pressure, permeability, existing stresses, and hydrological connectivity to deeper faults.

4. California regulations do not address the risks of induced earthquakes from wastewater injection wells or fracking.

Underground injection wells for oil and gas wastewater are regulated by the federal Safe Drinking Water Act's Underground Injection Control Program (UIC) and are classified as Class II wells. The EPA granted the State of California primacy to implement the UIC Class II program in California in 1982.[85] The federal UIC Class II regulations and California's UIC Class II program do not adequately address the risks of induced seismicity from wastewater injection wells.

Neither EPA's federal regulations for Class II wells nor California's UIC Class II program contain provisions specific to seismicity, and neither require operators to collect and submit the information needed to assess the risks of induced seismicity. Class II provisions can be compared to the UIC Class I program, which covers hazardous and non-hazardous waste from industrial and municipal sources.[86] Because wastewater from oil and gas production was exempted from hazardous waste regulations under the Resource Conservation and Recovery Act (RCRA), it is not classified as "hazardous" regardless of its composition and is not required to be disposed of under the more stringent requirements of the UIC Class I program.[87]

UIC Class I regulations include requirements for minimizing earthquake risk during well siting, including studies to demonstrate that the injection area has low background seismicity and that the proposed injection will not induce earthquakes.[88] Rules for Class I wells require geologic analysis of a much larger area surrounding each well to demonstrate that hazardous materials will not move out of the injection zone. They also mandate more stringent protocols for construction, operation, testing, and monitoring, as well as monitoring of the well and groundwater after the well is plugged. The weaker regulations for Class II wastewater injection wells may increase the risks of inducing earthquakes and contaminating drinking water.

Current DOGGR regulations for Class II wastewater injection wells are inadequate for protecting against the risks of induced earthquakes. The regulations related to earthquake risks only require that applications for injection projects include a map showing "reservoir characteristics such as… faults,"[89] without providing guidance on how to evaluate faults. Moreover, DOGGR only requires the industry to submit coarse-scale, monthly fluid injection volume and wellhead pressure data,[90] which makes it difficult to determine whether a particular wastewater injection well may have induced an earthquake.[91]

Notably, DOGGR does not require any seismic monitoring at or near wastewater injection wells, nor does it conduct any macro-level analysis — for multiple injection projects or on the field level — of the potential seismic impacts based on the planned or reported injection data.[92] All analysis of these data is on a project only level, which does not address any changes in seismic risk due to high concentrations of disposal well projects within a given field or area, or how neighboring injection projects interact on a cumulative level with surrounding faults.

In sum, although the regulations state that DOGGR should maintain data "to establish that no damage to life, health, property, or natural resources is occurring by reason of the project,"[93] DOGGR does not require the collection and assessment of the geological or fluid injection data needed to adequately evaluate the risks from induced earthquakes, or detect whether induced earthquakes are occurring.

Additionally, in July 2011, Environmental Protection Agency's Region 9 found DOGGR's implementation of its Class II program inadequate in several regards.[94] Specifically, the critique highlights DOGGR's one-size-fits-all Area of Review (AOR) standard that only requires review of a quarter-mile radius around the well, which could result in insufficient analysis of surrounding geologic features such as faults.[95] DOGGR has no systematic process for assessing geologic features outside of the quarter-mile AOR.[96] It appears that this process is ad-hoc and not adequate for identifying important geologic features outside of the quarter-mile radius AOR, and the potential for induced seismic events on faults more than a quarter-mile away from a disposal well. Due to the urgency of the identified deficiencies, the EPA requested that DOGGR provide an "action plan" to address them no later than September 1, 2011.[97] Despite the passage of more than two years, DOGGR has to date failed to bring its program into compliance with federal requirements.

DOGGR's November 2013 proposed regulations for well stimulation touch briefly on earthquake risks associated with well stimulation activities, but do not require any seismic monitoring to detect induced seismicity and mandate no action to respond to or potentially mitigate human-induced earthquakes.[98] The proposed regulations require the following:

- that evaluation prior to well stimulation include a review of all faults within a radius of twice the anticipated well-stimulation treatment length (Section 1784), and
- that the report submitted within 60 days of ending a well stimulation treatment will note if "data from the USGS indicates that, since the commencement of a well stimulation treatment, any earthquake of M2.0 or greater has occurred in the area of the well stimulation treatment radius" (Section 1789).[99]

In 2012, the National Academy of Sciences (NAS) recommended that states and regulators should take steps to prevent human-induced earthquakes.[100] The NAS panel was chaired by Colorado School of Mines professor Murray Hitzman, who cautioned that earthquakes associated with drilling can pose a risk to public health and safety.[101]

California oil and gas regulators have ignored these recommendations. State officials have said they don't need to look at injection wells and earthquakes, stating that the current rules are sufficient. In 2012, DOGGR spokesman Don Drysdale stated: "While seismicity is not specifically mentioned in the California Code of Regulations, DOGGR believes it is adequately addressed. Operators must evaluate oil and gas reservoirs prior to injection, and that evaluation includes faulting."[102] Not only has DOGGR failed to provide guidance or regulation that makes clear to the regulated community how to evaluate "faulting," the agency does not appear to have given much consideration to the risks associated with induced seismicity related to wastewater injection in California, or the risks of well-casing failure in areas that are notable for significant seismic activity.

5. The best way to protect Californians is to halt hydraulic fracturing, acidizing, and other unconventional oil and gas recovery techniques.

Fracking and other unconventional oil and gas extraction techniques are accompanied by numerous risks, including climate disruption, air and water pollution, public health impacts, the use of scarce water resources, and the production of billions of gallons of contaminated wastewater. New and ongoing research has established that much of the increased earthquake activity, and many of the large earthquakes in the Eastern and Midwestern U.S. where fracking-enabled oil and gas production has boomed, can be attributed to the underground injection of wastewater, providing yet more evidence of the negative consequences of fracking, acidizing, and other unconventional extraction techniques.

Our analysis of wastewater injection wells and faults in California found that 87 wastewater injection wells are within 1 mile of a recently active fault, 350 wells are within 5 miles, and 834 wells are within 10 miles. The proximity between many existing wastewater injection wells and recently active faults raises significant cause for concern over the potential for these wells to induce earthquakes.

In California, inadequate monitoring and research, fundamental knowledge gaps, and poor regulation indicate that Californians are not being protected from the earthquake risks posed by wastewater injection wells and fracking. Yet the state may be on the verge of rapid expansion of fracking and other techniques that will dramatically increase the use of wastewater injection wells.

California's current regulations do not adequately address the risks of induced earthquakes from wastewater injection wells and fracking. Additionally, California's proposed well stimulation regulations do almost nothing to reduce the risk of induced seismicity. The proposed DOGGR rules on well stimulation do not mandate the collection and assessment of data to proactively evaluate seismic risk during siting of wells, nor do they require seismic monitoring before, during, or after well operation or actions to respond to and mitigate potential induced-earthquake activity.

Induced earthquakes can impose large safety and economic costs on the public. Earthquakes induced by wastewater injection and fracking can affect a broad area beyond the well, causing damage to homes, workplaces, infrastructure, and potentially cause injury or devastating loss of human life. The public can also pay a high economic price. In response to the earthquake swarms occurring in Oklahoma, the state insurance commissioner recommended that Oklahomans buy earthquake insurance, which comes with prohibitive out-of-pocket costs to repair earthquake damage due to high deductibles,[103] as well as skyrocketing insurance rates near earthquake epicenters.[104]

Through inaction and failure to address the potential risks, the state has in effect transferred to the public many of the potential risks and costs associated with induced seismicity, well-casing failure, and associated leaks that might be caused by earthquakes. Without effective monitoring or regulatory systems in place, those harmed by property damage, water contamination, or other harm will likely face daunting challenges to demonstrating that oil and gas operations caused the harm. By failing to require adequate monitoring and through lack of oversight, California's Department of Conservation fails to comply with its legal mandate to protect public safety and welfare. Furthermore, the state enables companies that profit from oil and gas production to transfer the risks associated with seismicity to the public.

It has been suggested that earthquake risks from wastewater injection wells can be managed if the industry follows a strict series of steps for study and planning prior to injection, performs monitoring in areas where seismicity might be triggered, and establishes protocols for responding, including potential well abandonment if induced seismicity occurs.[105] Existing and proposed California regulations do not require oil and gas operators to take any of these steps. Instituting this system would require far-reaching changes to business-as-usual practices that work in the industry's favor.

Implementing the best-possible system to monitor and manage earthquake risks from wastewater injection wells and fracking could reduce — but not eliminate — the risks to Californians. There are significant technological and cost limitations for locating faults and characterizing geology, as well as large knowledge gaps, which limit the ability to effectively address the risks. Moreover, even the best monitoring and management system would still place safety and economic burdens on the public. Due to these limitations, DOGGR cannot safely regulate induced seismicity.

In light of the known environmental and health risks from unconventional extraction and wastewater disposal, the link between wastewater injection wells and earthquakes in other states, the potential for a huge expansion of drilling and wastewater production in the Monterey Shale, and the gaps in scientific knowledge regarding induced seismicity, the best way to protect Californians is to halt hydraulic fracturing, acidizing, and other unconventional oil and gas recovery techniques. Moreover, no oil and gas wastewater disposal should be allowed that does not account for all risks, including seismic risks.

Acknowledgements

We would like to thank our supporters for their generosity. We would like to thank the FracTracker Alliance for developing the California Geological Hazards Map, and the Injection Wells and Hydraulic Fracturing in California's Fault Zones maps. We also thank Curt Bradley (Center for Biological Diversity) for assistance with the GIS analyses.

Appendix A: Research and Methodology

The data used to generate the "California Geological Hazards" and "Injection Wells and Hydraulic Fracturing in California's Fault Zones" maps on FracMapper come from several sources, including DOGGR, CGS, and USGS. Several map layers were downloaded as shapefiles and imported directly into ArcGIS without amendments, while other datasets were aggregated, queried or significantly edited to produce the map layers.

The well-site locations were downloaded as the full DOGGR dataset, available as "AllWells.zip." The DOGGR database was queried to separate the individual well-types into the various map layers, and differentiate between new, active, idle, plugged, and buried wells. "New" wells have been permitted, but have not yet been drilled. The permit is valid for one year, or up to two years upon request. The database includes an identifier for hydraulically fractured wells; these wells were isolated and then combined with the SkyTruth.org database of hydraulically fractured wells, which they extract from FracFocus.org. The hybrid dataset can be downloaded from FracTracker (CA Hydraulically Fractured Wells). An additional well-site database showing well sites within the South Coast Air Quality Monitoring District is also projected in the maps. The California high-magnitude quaternary faults map layer was generated by clipping the USGS dataset for the entire United States. The dataset of "Named California Faults" also used for the proximity analysis was retrieved from CGS. The Hayward fault shapefile was downloaded from USGS as a package also containing landslide hazard zones. The "Named Faults" dataset that was used for part of the proximity analysis was produced by eliminating all unnamed quaternary fault-lines from the CGS fault database.

The statewide shaking hazards map layers estimate the amplification based on the underlying geology of the soil. A research group consisting of both USGS and CGS geologists developed risk hazards available as shapefiles for both high frequency and low frequency seismic events. High frequency shaking poses a hazard for short building structures, while low frequency shaking is the most hazardous to large multi-story cityscape buildings. For the Bay Area and East Bay, additional shaking hazards analyses have been completed. Liquefaction risks have been estimated by USGS and CGS specifically for the Bay Area, Alameda County and multiple fault-slip scenarios for Santa Clara in separate assessments. All shapefiles are viewable individually in the California Geological Hazards Map.

There are no regional liquefaction risk estimate maps available outside of the Bay Area, although the CGS has identified regions of liquefaction and landslide hazards zones for the metropolitan areas surrounding the Bay Area and Los Angeles. These maps outline the areas where liquefaction and landslides can be expected given a standard set of conservative assumptions. These datasets are only available via individual 7.5-minute quadrangles. To produce the map layers FracTracker aggregated the quadrangles, and combined the data into unified datasets, downloadable here; Landslide and Liquefaction.

For the proximity analysis of Class II wastewater injection wells and faults, we used the most recently updated dataset from DOGGR, posted 9/27/13, which identified 2,583 total Class II water injection wells. Of those, 2,578 entries had latitude/longitude data, with 1,473 wells listed as "active," 80 listed as "new," and 1,031 listed as "plugged." The proximity analysis included the 1,553 wells listed as "active" or "new. "We used the North American Datum 1983 State Plane California IV FIPS 0404 projection because the majority of Class II Water Disposal wells are located in Kern County. The analysis was conducted using ESRI's ArcGIS ArcMap V. 10.1 software. We used two fault databases: (1) the California Geological Survey 2010 Fault Activity Map of California, and (2) the U.S. Geological Survey Quaternary Fault and Fold Database of the U.S. Buffers were created around the Class II Injection Well shapefiles, and the 'intersect' function was used to generate the proximity datasets. Database management was conducted using IBM SPSS Statistics v.20 software.

Appendix B: Analysis of the Distances of All (Active, New, Idle, Plugged, and Buried) Class II Injection Wells to Faults

This Appendix presents analyses similar to those presented for active and new Class II wastewater injection wells, but includes both active and inactive wastewater injection wells, including active, new, idle, plugged, and buried wells, totaling 2,578 wells with location data.

Our analysis shows that 1,177 (46 percent) of California's 2,578 active and inactive wastewater injection wells are within 10 miles of a recently active fault that has caused an earthquake in the past 200 years, 527 wells (20 percent) are within 5 miles, and 112 wells (4 percent) are within 1 mile (Table 1). Of added concern, 115 wells are within 10 miles of a recently active, high-magnitude fault that has caused an earthquake greater than M6 in the past 150 years, 94 wells are within 5 miles, and 3 wells are within 1 mile.

When all faults are considered, our analysis found that 1,936 active and inactive wastewater injection wells (75 percent) are within 10 miles of a Quaternary fault, 1,422 wells (55 percent) are within 5 miles, and 527 wells (20 percent) are within 1 mile (Table 2). Of these, 1,001 wells are within 10 miles of a high-magnitude Quaternary fault that has caused an earthquake greater than M6 in the past 1.6 million years, 606 wells are within 5 miles, and 135 wells are within 1 mile.

TABLE 1. Number of active and inactive wastewater injection wells within 1, 5, and 10 miles of recently active faults that have caused earthquakes in the past 200 years

NUMBER OF WELLS (PERCENT)	**DISTANCE TO FAULT**
112 (4%)	Within 1 mile
527 (20%)	Within 5 miles
1,177 (46%)	Within 10 miles

TABLE 2. Number of active and inactive wastewater injection wells within 1, 5, and 10 miles of Quaternary faults that have caused earthquakes in the past 1.6 million years

NUMBER OF WELLS	**DISTANCE TO FAULT**
527 (20%)	Within 1 mile
1,422 (55%)	Within 5 miles
1,936 (75%)	Within 10 miles

References

[1] U.S. Environmental Protection Agency (EPA).(2000). Profile of the Oil and Gas Extraction Industry (EPA/310-R-99-006). Office of Enforcement and Compliance Assurance. Retrieved from website: http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/oilgas.pdf

[2] Collier, R. (2013). Part 1: Distracted by Fracking? Next Generation. Retrieved from website: http://thenextgeneration.org/files/Acidizing_Part_1_Final.pdf

[3] Processing Magazine. (2013). California Drillers Prefer Acidizing Over Fracking. 13 August 2013. Accessed at website: http://www.processingmagazine.com/articles/126028-california-drillers-prefer-acidizing-over-fracking

[4] Lustgarten, A. (2009). In new gas wells, more drilling chemicals remain underground. ProPublica. Retrieved from website: http://www.propublica.org/article/new-gas-wells-leave-more-chemicals-in-ground-hydraulic-fracturing; McSurdy, S. and R. Vidic. (2009). Sustainable Management of Flowback Water During Hydraulic Fracturing of Marcellus Shale for Natural Gas Production (DE-FE0000975). U.S. Department of Energy, National Energy Technology Laboratory. Retrieved from website: http://www.netl.doe.gov/technologies/oil-gas/Petroleum/projects/Environmental/Produced_Water/00975_MarcellusFlowback.html; U.S. Department of Energy (DOE). (2009). Modern Shale Gas Development in the United States: A Primer (April 2009). Retrieved from website: http://www.eogresources.com/responsibility/doeModernShaleGasDevelopment.pdf

[5] Colborn, T. et al. (2011). Natural gas operations from a public health perspective. Human and Ecological Risk Assessment 17: 1039-1056. Retrieved from website: http://cce.cornell.edu/EnergyClimateChange/NaturalGasDev/Documents/PDFs/fracking%20chemicals%20from%20a%20public%20health%20perspective.pdf

[6] U.S. Government Accountability Office (GAO). (2012). Information on the Quantity, Quality, and Management of Water Produced During Oil and Gas Production. United States Government Accountability Office (January 2012.) Retrieved from website: http://www.gao.gov/assets/590/587522.pdf

[7] U.S. Government Accountability Office (GAO). (2012)

[8] Cooley, H. and K. Donnelly. (2012). Hydraulic fracturing and water resources: separating the frack from the fiction. Pacific Institute, Oakland, CA. (June 2012). Retrieved from website: http://www.pacinst.org/wp-content/uploads/2013/02/full_report35.pdf

[9] California Department of Conservation. (2011). Producing Wells and Production of Oil, Gas, and Water by County – 2011. Retrieved from website: ftp://ftp.consrv.ca.gov/pub/oil/temp/NEWS/Producing_Wells_OilGasWater_11.pdf

[10] Cooley, H. and K. Donnelly. (2012); Tyrell, J.P. et al. (2013) Management of produced water from oil and gas wells in California: past trends and future suggestions. 2013 GSA Annual Meeting in Denver: 27-30 October 2013; U.S. Government Accountability Office (GAO). (2012)

[11] U.S. Environmental Protection Agency (EPA). (2012). Minimizing and Managing Potential Impacts of Induced-Seismicity from Class II Disposal Wells: Practical Approaches. Underground Injection Control National Technical Working Group. Draft. (November 27, 2012). Retrieved from website: http://www.eenews.net/assets/2013/07/19/document_ew_01.pdf.

According to the U.S. EPA website (http://water.epa.gov/type/groundwater/uic/class2/) there are approximately 144,000 Class II wells in operation in the US, injecting over 2 billion gallons of wastewater everyday. Most of these are located in Texas, California, Oklahoma, and Kansas. Three types of Class II wells are associated with the industry: 1) Enhanced recovery wells – flowback fluids, along with other liquids and gases are injected to recover residual oil and gas. This is known as secondary or tertiary recovery. These are the most common type, accounting for nearly 80% of all Class II wells. 2) Disposal wells – flowback fluids are injected into the same, or similar, formations as the well from which it was extracted. Disposal wells account for approximately 20% of all Class II wells. 3) Hydrocarbon storage wells – these serve as underground storage for hydrocarbons, and are found in formations (such as salt caverns). The main use of these wells if for the US Strategic Petroleum Reserve. There are over 100 hydrocarbon storage wells in operation.

[12] California Department of Conservation. (1982). Underground Injection Control Memorandum of Agreement Between California Division of Oil and Gas and The United States Environmental Protection Agency Region 9. Retrieved from website: http://www.conservation.ca.gov/dog/for_operators/Documents/MOU-MOA/MOA_EPA_UIC_1982.pdf

[13] U.S. Environmental Protection Agency. (2014). *Class II Wells – Oil and Gas Related Injection Wells*. Accessed at website: http://water.epa.gov/type/groundwater/uic/class2/; U.S. Environmental Protection Agency. (2012)

[14] Railroad Commission of Texas. (2013). *Saltwater Disposal Wells Frequently Asked Question (FAQs)*. Updated 06.25.13. Accessed at website: http://www.rrc.state.tx.us/about/faqs/saltwaterwells.php.

[15] National Public Radio. (2013). *Exploring the link between earthquakes and oil and gas disposal wells*. National Public Radio, State Impact Oklahoma. Accessed at website: http://stateimpact.npr.org/oklahoma/tag/earthquakes/

[16] California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR). AllWells.zip database. Updated 27 September 2013. Accessed 8 November 2013. ftp://ftp.consrv.ca.gov/pub/oil/GIS/Shapefiles/

---

[17] California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR). AllWells.zip database. Updated 27 September 2013. Accessed 8 November 2013. ftp://ftp.consrv.ca.gov/pub/oil/GIS/Shapefiles/

[18] California Department of Conservation, DOGGR. (2014). *Oil, Gas & Geothermal-Injection Wells*. Accessed at website: http://www.conservation.ca.gov/dog/general_information/Pages/class_injection_wells.aspx

[19] California Department of Conservation, DOGGR. (2013). 2012 Preliminary Report of Oil and Gas Production Statistics (April 2013). Retrieved from website: ftp://ftp.consrv.ca.gov/pub/oil/annual_reports/2012/PR03_PreAnnual_2012.pdf

[20] Clark, C.E. and J.A. Veil. (2009). Produced water volumes and management practices in the United States. Prepared by the Argonne National Laboratory for the U.S. Department of Energy. Retrieved from website: www.osti.gov/bridge

[21] Clark, C.E. and J.A. Veil. (2009)

[22] Clark, C.E. and J.A. Veil. (2009); Tyrell, J.P. et al. (2013)

[23] Henry, T. and K. Galbraith. (2013). *Fracking disposal wells pose challenges in Texas*. National Public Radio, State Impact Texas, 29 March 2013. Accessed at website: http://stateimpact.npr.org/texas/2013/03/29/fracking-disposal-wells-pose-challenges-in-texas/

[24] U.S. Energy Information Administration (EIA). (2012). Annual Energy Outlook 2012 with Projections to 2035. DOE/EIA-0383(2012). U.S. Department of Energy, Washington, DC. Table 16. Retrieved from website: http://www.eia.gov/forecasts/archive/aeo12/pdf/0383%282012%29.pdf

[25] National Research Council (NRC). (2012). Induced Seismicity Potential in Energy Technologies. National Academies Press. Retrieved from website: http://www.nap.edu/catalog.php?record_id=13355

[26] Ellsworth, W.L. (2013). Injection-induced earthquakes. Science 341: 1225942

[27] National Research Council (NRC). (2012)

[28] Ellsworth, W.L. (2013)

[29] Ellsworth, W.L. (2013)

[30] Ellsworth, W.L. (2013)

[31] The moment magnitude scale, abbreviated here as M, measures the size of earthquakes in terms of the energy released. M2.5 earthquakes and larger can be felt at the surface, while earthquakes at M4 and larger can cause damage to structures and cause human injuries.

[32] Ellsworth, W.L. (2013)

[33] Ellsworth, W.L. (2013); Associated Press. (2010). *W.Va. Studying link between earthquakes and wells*. Charleston Daily Mail. 8 September 2010. Accessed at website: http://www.charlestondailymail.com/News/statenews/201009010376?src=savethewatertable.org

[34] Ellsworth, W.L. (2013); Keranen, K.M. et al. (2013). Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 M_w 5.7 earthquake sequence. Geology 41: 699–702

[35] Llenos, A.L. and A.J. Michael. (2013). Modeling earthquake rate changes in Oklahoma and Arkansas: possible signatures of induced seismicity. Bulletin of the Seismological Society of America 103: 2850-2861

[36] U.S. Geological Survey (USGS). (2013). Earthquake Swarm continues in central Oklahoma. Press release, 22 October 2013. Retrieved from website: http://www.usgs.gov/newsroom/article.asp?ID=3710

[37] Wertz, J. (2013). *Oklahomans live with shaking as researchers study earthquake swarm*. National Public Radio, State Impact Oklahoma, 14 November 2013. Accessed at website: http://stateimpact.npr.org/oklahoma/2013/11/14/oklahomans-live-with-shaking-as-researchers-study-earthquake-swarm/

[38] Keranen, K.M. et al. (2013). Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 M_w 5.7 earthquake sequence. Geology 41: 699–702

[39] U.S. Geological Survey (USGS). (2013). Earthquake Swarm continues in central Oklahoma. Press release, 22 October 2013. Retrieved from website: http://www.usgs.gov/newsroom/article.asp?ID=3710

[40] Oklahoma Insurance Department. (2013). Commissioner Doak Encourages Homeowners to Purchase Earthquake Insurance. Accessed at website: http://www.ok.gov/triton/modules/newsroom/newsroom_article.php?id=157&article_id=12955

[41] Soraghan, M. (2013). *10% of U.S. earthquakes are in Okla. Is drilling to blame?* E&E Publishing, 2 December 2013. Accessed at website: http://www.eenews.net/energywire/stories/1059991119

[42] Frohlich, C. and M. Brunt. (2013). Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the M_w4.8 20 October 2011 earthquake. Earth and Planetary Science Letters 379: 56-63

---

[43] Brown, W.A. et al. (2012). The May 17th, 2012 M4.8 earthquake near Timpson, east Texas: Was it natural or was it induced?, Abstract S53I-06 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec.; Brown, W.A. and C. Frohlich. (2013). Investigating the cause of the 17 May 2012 M 4.8 earthquake near Timpson, east Texas (abstr.). Seismoloical Research Letters 84: 374; Frohlich, C. and M. Brunt. (2013)

[44] Buchele, M. (2013). *A Labor Day of earthquakes for Timpson, Texas*. National Pubic Radio, State Impact Texas, 3 September 2013. Accessed at website: http://stateimpact.npr.org/texas/2013/09/03/a-labor-day-of-earthquakes-for-timpson-texas/

[45] Frohlich, C. et al. (2011). The Dallas–Fort Worth earthquake sequence: October 2008 through May 2009. Bulletin of the Seismological Society of America 101: 327–340

[46] Henry, T. (2013). *How fracking disposal wells are causing earthquakes in Dallas-Ft. Worth*. National Public Radio, State Impact Texas, 6 August 2013. Accessed at website: http://stateimpact.npr.org/texas/2012/08/06/how-fracking-disposal-wells-are-causing-earthquakes-in-dallas-fort-worth/

[47] Rubinstein, J.L., et al. (2012). The 2001–present triggered seismicity sequence in the Raton Basin of southern Colorado/northern New Mexico, Abstract S34A-02 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec

[48] Horton, S. (2012). Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in Central Arkansas with potential for damaging earthquake. Seismological Research Letters 83: 250-260; Llenos, A.L. and A.J. Michael. (2013)

[49] Horton, S. (2012); Llenos, A.L. and A.J. Michael. (2013)

[50] Kim, W-Y. (2013). Induced Seismicity Associated with Fluid Injection into a Deep Well in Youngstown, Ohio, Journal of Geophysical Research: Solid Earth 118: 3506–3518

[51] Keranen, K.M. et al. (2013)

[52] Ellsworth, W.L. (2013)

[53] Ellsworth, W.L. (2013)

[54] Ellsworth, W.L. (2013)

[55] Holland, A.A. (2013). Earthquakes triggered by hydraulic fracturing in south-central Oklahoma. Bulletin of the Seismological Society of America 103: 1784-1792

[56] BC Oil and Gas Commission. (2012). Investigation of observed seismicity in the Horn River Basin. BC Oil and Gas Commission, Victoria, British Columbia, Canada. Retrieved from website: www.bcogc.ca/node/8046/download?documentID=1270

[57] Green, C.A. and P. Styles. (2012). Preese Hall shale gas fracturing: Review and recommendations for induced seismicity mitigation. Retrieved from website: www.gov.uk/government/uploads/

[58] Ingraffea, A. R. (2013) Fluid Migration Mechanisms Due to Faulty Well Design and/or Construction: an Overview and Recent Experiences in the Pennsylvania Marcellus Play. January2013. Retrieved from website: http://www.psehealthyenergy.org/data/PSE__Cement_Failure_Causes_and_Rate_Analaysis_Jan_2013_Ingraffea1.pdf

[59] Lustgarten, A. (2012). *Injection Wells: the Poison Beneath Us*. ProPublica, 22 June 2012. Accessed at website: http://www.propublica.org/article/injection-wells-the-poison-beneath-us

[60] ProPublica. (2012). *State by State: Underground Injection Wells*. 20 Sept 2012. Accessed at website: http://projects.propublica.org/graphics/underground-injection-wells

[61] California Department of Conservation, Division of Oil Gas and Geothermal Resources. (2007). 2006 Annual Report of the State Oil & Gas Supervisor, p. 26. Retrieved from website: ftp://ftp.consrv.ca.gov/pub/oil/annual_reports/2006/2006AnnualReport.pdf

[62] California Department of Conservation. (2007). API 11101020 well record. Retrieved from website: ftp://ftp.consrv.ca.gov/pub/oil/WellRecord/111/11101020/11101020_DATA_09-27-2007.pdf

[63] U.S. Geological Survey. (2012). *Earthquake Glossary - Ring of Fire.* Accessed from website: http://earthquake.usgs.gov/learn/glossary/?termID=150

[64] U.S. Geological Survey. (2013). *The San Andreas Fault.* Accessed at website: http://pubs.usgs.gov/gip/earthq3/contents.html

[65] U.S. Geological Survey. (2014). *California, Earthquake History*. Accessed at website: http://earthquake.usgs.gov/earthquakes/states/california/history.php; U.S. Geological Survey. (2013). *Mendocino Triple Junction Offshore Northern California.* Accessed at website: http://woodshole.er.usgs.gov/operations/obs/rmobs_pub/html/mendocino.html

[66] Folger, P. (2013). Earthquakes: Risk, Detection, Warning, and Research. Congressional Research Service. 7-5700. July 18, 2013. Retrieved from website: www.crs.gov

[67] Folger, P. (2013)

---

[68] U.S. Geological Survey. (2008). Forecasting California's Earthquakes – What Can We Expect in the Next 30 Years? USGS Fact Sheet 2008-3027. Retrieved from website: http://pubs.usgs.gov/fs/2008/3027/fs2008-3027.pdf

[69] U.S. Geological Survey. (2006). *About Liquefaction*. Accessed at website: http://geomaps.wr.usgs.gov/sfgeo/liquefaction/aboutliq.html

[70] U.S. Geological Survey. (2012). *Liquefaction Susceptibility.* Accessed at website: http://earthquake.usgs.gov/regional/nca/bayarea/liquefaction.php

[71] U.S. Geological Survey. (2006). *About Liquefaction*. Accessed at website: http://geomaps.wr.usgs.gov/sfgeo/liquefaction/aboutliq.html

[72] California Geological Survey (CGS). 2010 Fault Activity Map. Accessed at website: http://www.consrv.ca.gov/cgs/cgs_history/Pages/2010_faultmap.aspx. Data provided by CGS.

[73] U.S. Geological Survey (USGS). Quaternary Fault and Fold Database of the US. Accessed at website: http://earthquake.usgs.gov/hazards/qfaults/download.php

[74] Ellsworth, W.L. (2013)

[75] National Research Council (NRC). (2012)

[76] Chen, R. and C.J. Wills (2011). HAZUS Annualized Earthquake Loss Estimation for California. Department of Conservation, California Geological Survey. Retrieved from website: http://www.conservation.ca.gov/cgs/rghm/loss/Pages/2010_analysis.aspx

[77] Chen, R. and C.J. Wills (2011)

[78] Jones, L.M. et al. (2008). The Shakeout Scenario. USGS Open File Report 2008-1150. U.S. Department of the Interior, U.S. Geological Survey. Retrieved from website: http://www.conservation.ca.gov/cgs/information/publications/sr/Documents/PR25.pdf

[79] 14 CCR § 1724.7(c)

[80] 14 CCR § 1724.10(h)

[81] DOGGR, personal communication, Jan 8, 2014, Mike Cummings

[82] California Integrated Seismic Network (CISN). Accessed at website: http://www.cisn.org/

[83] CISN Program Management Group. (2011). California Integrated Seismic Network Strategic Plan: 2011-2016. Retrieved from website: http://www.cisn.org/program/CISN_strat_plan_yr11_16_v06.pdf

[84] Fossen, H. (2010). Structural Geology, Cambridge University Press. p. 356

[85] California Department of Conservation. (1982). Underground Injection Control Memorandum of Agreement Between California Division of Oil and Gas and The United States Environmental Protection Agency Region 9. Retrieved from website: http://www.conservation.ca.gov/dog/for_operators/Documents/MOU-MOA/MOA_EPA_UIC_1982.pdf

[86] U.S. Environmental Protection Agency (EPA). *Requirements for all Class I Wells and Class I Hazardous Waste Wells.* Retrieved from website: http://www.epa.gov/ogwdw/uic/pdfs/page_uic-class1_summary_class1_reqs.pdf

[87] Cooley, H. and K. Donnelly. (2012)

[88] U.S. Environmental Protection Agency (EPA). *Requirements for all Class I Wells and Class I Hazardous Waste Wells.* Retrieved from website: http://www.epa.gov/ogwdw/uic/pdfs/page_uic-class1_summary_class1_reqs.pdf

[89] 14 CCR § 1748.2(c)

[90] DOGGR, personal communication, Jan 8, 2014, Mike Cummings

[91] Ellsworth, W.L. (2013).

[92] DOGGR, personal communication, Jan 23, 2014, Tim Kustic, Oil and Gas Supervisor and Jerry Salera, UIC Program Manager

[93] 14 CCR § 1724.10(h)

[94] U.S. Environmental Protection Agency (EPA). (2011). July 18, 2011 letter from EPA to Elena Miller, State Oil and Gas Supervisor, Department of Conservation, Division of Oil, Gas, and Geothermal Resources

[95] Horsley Witten Group. (2011). California Class II Underground Injection Control Program Review. June 2011. Retrieved from website: ftp://ftp.consrv.ca.gov/pub/oil/fullreport.pdf

[96] DOGGR, personal communication, Jan 23, 2014. Tim Kustic, Oil and Gas Supervisor and Jerry Salera, UIC Program Manager

[97] U.S. Environmental Protection Agency (EPA). (2011). July 18, 2011 letter from EPA to Elena Miller, State Oil and Gas Supervisor, Department of Conservation, Division of Oil, Gas, and Geothermal Resources. p. 2

---

[98] DOGGR. (2013). SB4 Well Stimulation Treatment Regulations. Text of Proposed Regulations. Chapter 4. Development, Regulation, and Conservation of Oil and Gas Resources. Retrieved from website: http://www.conservation.ca.gov/index/Documents/Text%20of%20Proposed%20Regulations%20-%20SB%204%20Well%20Stimulation%20Treatment%20Regulations.pdf

[99] DOGGR. (2013). SB4 Well Stimulation Treatment Regulations. Text of Proposed Regulations. Chapter 4. Development, Regulation, and Conservation of Oil and Gas Resources. Retrieved from website: http://www.conservation.ca.gov/index/Documents/Text%20of%20Proposed%20Regulations%20-%20SB%204%20Well%20Stimulation%20Treatment%20Regulations.pdf

[100] National Research Council (NRC). (2012)

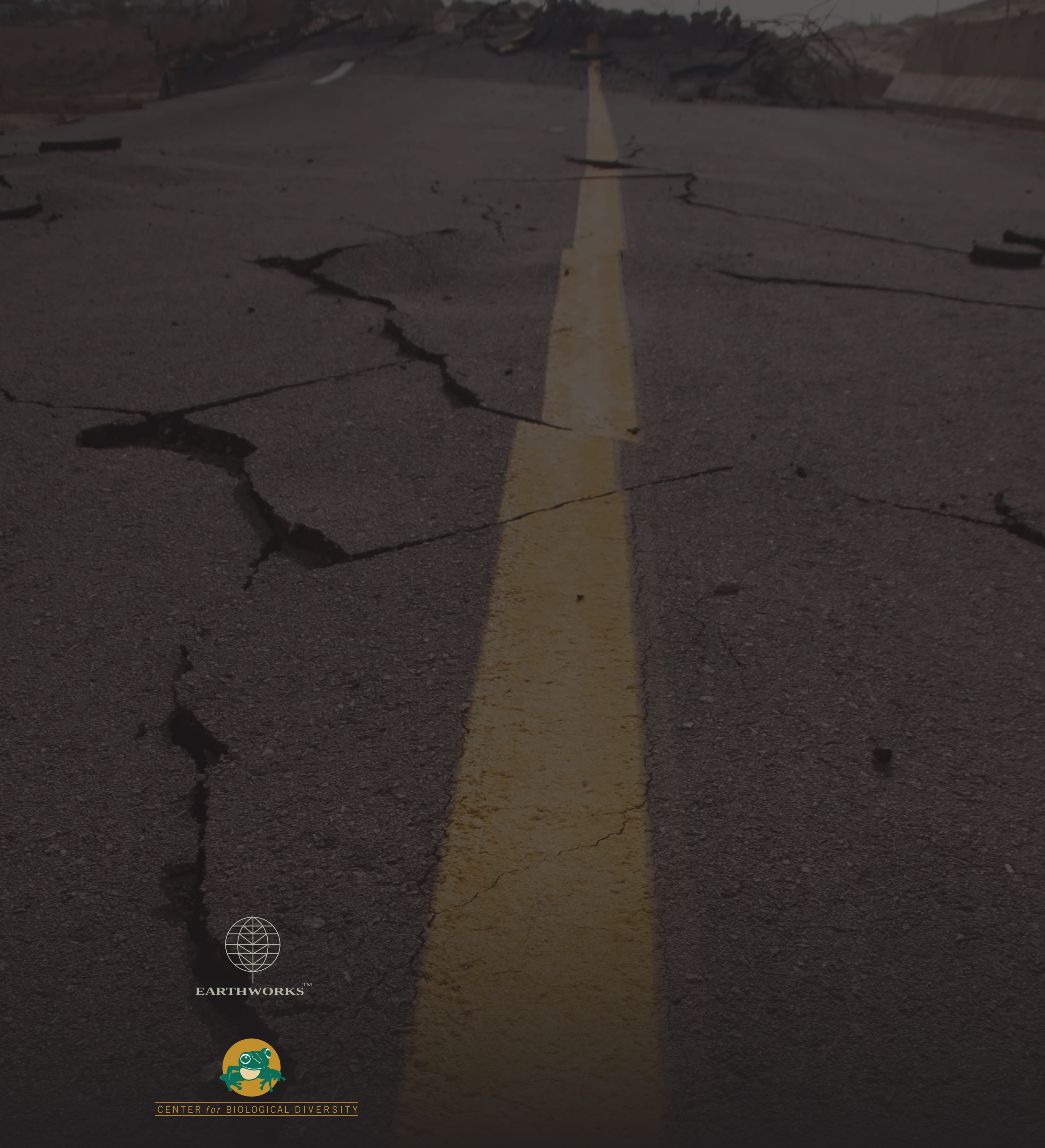
[101] Soraghan, M. (2013). *Earthquakes: States deciding not to look at seismic risks of drilling*. E&E Publishing, 25 March 2013. Accessed at website: http://www.eenews.net/stories/1059978378

[102] Soraghan, M. (2013). *Earthquakes: States deciding not to look at seismic risks of drilling*. E&E Publishing, 25 March 2013. Accessed at website: http://www.eenews.net/stories/1059978378

[103] Wertz, J. (2013). *Five things Oklahomans need to know about earthquake insurance*. National Public Radio, State Impact Texas, 18 November 2013. Accessed at website: http://stateimpact.npr.org/oklahoma/2013/11/18/five-things-oklahomans-need-to-know-about-earthquake-insurance/

[104] Soraghan, M. (2013). *Okla. official recommends quake insurance to residents.* E&E Publishing, 31 October 2013. Accessed at website: http://www.eenews.net/energywire/stories/1059989714/search?keyword=oklahoma+earthquake+and+insurance

[105] Zoback, M.D. (2012). Managing the seismic risk posed by wastewater disposal. *Earth Magazine*. April 2012



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