



Liquid carbon dioxide has been injected into the Sleipner gas- and oilfield in the North Sea for 15 years without triggering any seismicity. It serves as a good example of how fluid injection can be done safely.

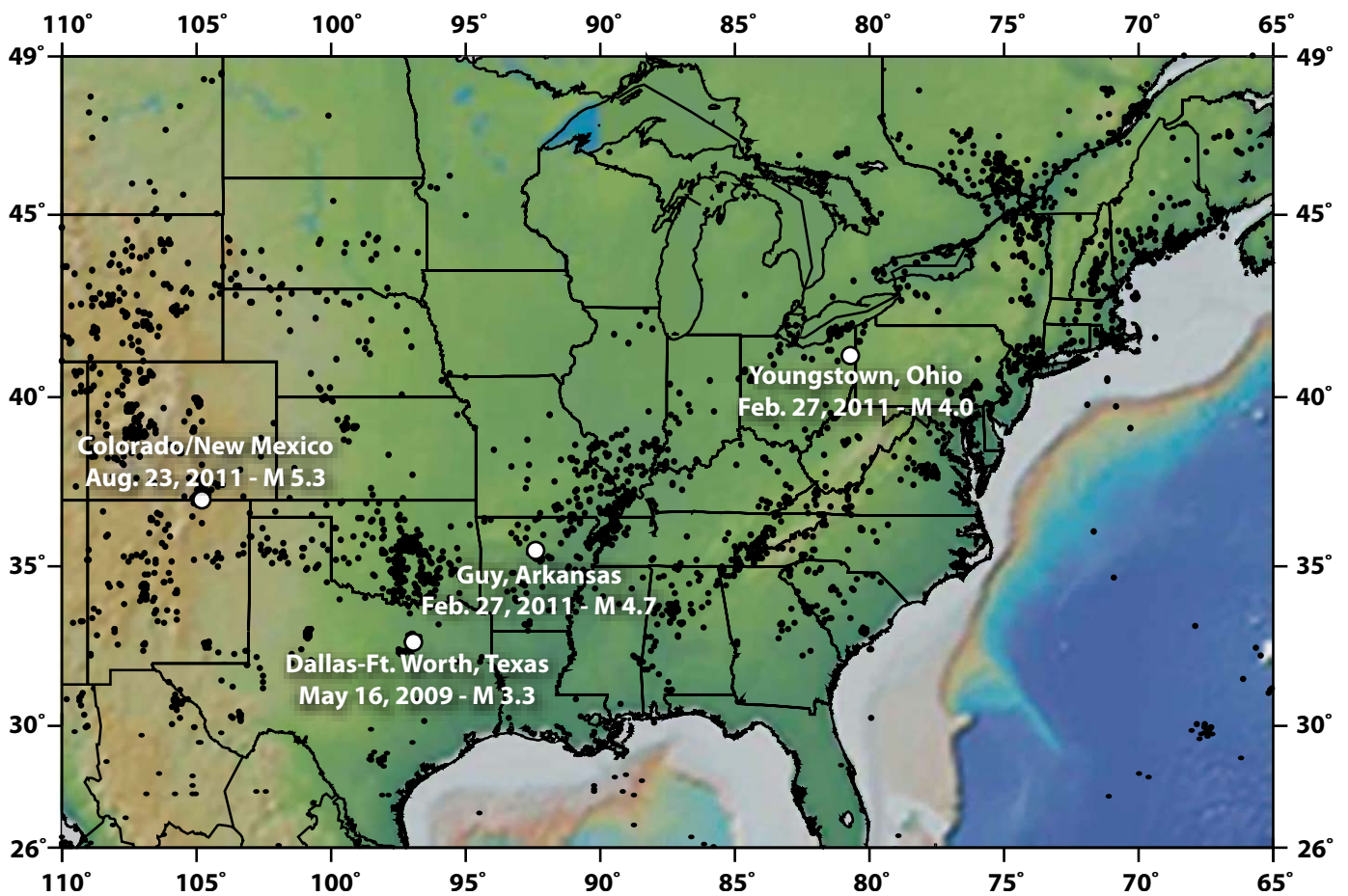
Managing the Seismic Risk Posed by Wastewater Disposal

Mark D. Zoback

From an earthquake perspective, 2011 was a remarkable year. While the devastation accompanying the magnitude-9.0 Tohoku earthquake that occurred off the coast of Japan on March 11 still captures attention worldwide, the relatively stable interior of the U.S. was struck by a somewhat surprising number of small-to-moderate earthquakes that were widely felt. Most of these were natural events, the types of earthquakes that occur from time to time in all intraplate regions. For example, the magnitude 5.8 that occurred in central Virginia on Aug. 23 was felt throughout the northeast, damaged the Washington Monument, and caused the temporary shutdown of a nuclear power plant. This earthquake occurred in the Central

Virginia Seismic Zone, an area known to produce relatively frequent small earthquakes.

However, a number of the small-to-moderate earthquakes that occurred in the U.S. interior in 2011 appear to be associated with the disposal of wastewater, at least in part related to natural gas production. Several small earthquakes were apparently caused by injection of wastewater associated with shale gas production near Guy, Ark.; the largest earthquake was a magnitude-4.7 event on Feb. 27. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of wastewater associated with coalbed methane production seems to be associated with a magnitude-5.3 event that occurred on Aug. 22, and small earthquakes that appear to have been triggered by



Earthquakes above magnitude-3.0 have been recorded by the U.S. Geological Survey in the Central and Eastern United States and southeastern Canada since 1960. The dates and largest magnitudes associated with recent earthquakes apparently triggered by fluid injection are noted.

wastewater injection occurred on Christmas Eve and New Year's Eve near Youngstown, Ohio, the largest of which was a magnitude 4.0. Although there has been speculation that the magnitude-5.6 earthquake that occurred in Oklahoma on Nov. 5 may have been triggered by similar fluid injection, no linkage between this earthquake and fluid injection has been established.

The occurrence of injection-related earthquakes is understandably of concern to the public, government regulators, policymakers and industry alike. Yet it is important to recognize that with proper planning, monitoring and response, the occurrence of small-to-moderate earthquakes associated with fluid injection can be reduced and the risks associated with such events effectively managed.

First, the Facts

No earthquake triggered by fluid injection has ever caused serious injury or significant damage. Moreover, approximately 140,000 wastewater disposal wells have been operating safely and without incident in the U.S. for many decades.

That said, we have known for more than 40 years that earthquakes can be triggered by

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fluid injection. The first well-studied cases were earthquakes triggered by waste disposal at the Rocky Mountain arsenal near Denver, Colo., in the early 1960s, and by water injection at the Rangely oilfield in western Colorado in the late '60s and early '70s.

Such quakes occur when increasing pore pressure at depth caused by fluid injection reduces the effective normal stress acting perpendicular to pre-existing faults. The effective normal stress on a fault can be thought of as a force that resists shear movement — much as how putting a weight on a box makes it more difficult to slide along the floor. Increasing pore pressure reduces the effective normal stress, allowing elastic energy already stored in brittle rock formations to be released in earthquakes. These earthquakes would someday have occurred anyway as a result of slowly accumulating forces in the earth resulting from natural geologic processes — injection just speeds up the process.

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As there has been an appreciable increase in hydraulic fracturing associated with shale gas development in recent years, it should be pointed out that the water injection associated with hydraulic fracturing is not responsible for the triggered seismicity in question. The reason for this is that pressurization during hydraulic fracturing affects only limited volumes of rock (typically several hundred meters in extent) and pressurization typically lasts only a few hours. Thus, while very small earthquakes have occurred during hydraulic fracturing (such as a magnitude-2.3 earthquake near Blackpool, England, in April 2011), these are extremely rare events. The concern about triggered seismicity associated with shale gas development arises after hydraulic fracturing, when wastewater that flows back out of the wells is disposed of at dedicated injection wells.

Five straightforward steps can be taken to reduce the probability of triggering seismicity whenever we inject any fluid into the subsurface. First, it is important to avoid injection into active faults and faults in brittle rock. Second, formations should be selected for injection (and injection rates should be limited) to minimize pore pressure changes. Third, local seismic monitoring arrays should be installed when there is a potential for injection to trigger seismicity. Fourth, protocols should be established in advance to define how operations will be modified if seismicity is triggered. And fifth, operators need to be prepared to reduce injection rates or abandon wells if triggered seismicity poses any hazard. These five steps provide regulators and operating companies with a framework for reducing the risk associated with triggered earthquakes.

Step 1: Avoid Injection into Active Faults

Aside from plate boundaries where large earthquakes occur with regularity, earthquakes also occur in brittle rocks nearly everywhere within continental interiors around the world as a result of natural geologic processes. It is thus no surprise that fluid injection occasionally triggers earthquakes. In fact, building dams for surface reservoirs occasionally triggers small- to moderate-sized earthquakes even though resultant pore pressure increases at depth are extremely small.



Shale gas and tight oil are produced in the Bakken Formation in North Dakota.

Modern 3-D seismic imaging methods are sufficiently advanced that we can identify faults capable of producing potentially damaging earthquakes at depth. Faults large enough to produce damaging earthquakes — say, those above magnitude 6.0 — should be easily detectable as part of geologic characterization studies of potential injection sites because they are associated with slip on faults that are many tens of kilometers in size. Smaller faults may be harder to detect, but will only produce small earthquakes that might be felt locally but will not cause damage.

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We also know a lot about the relationship between the orientation of potentially active faults and the ambient stress field in a given region. This also enables us to identify (and avoid) potentially problematic faults prior to injection. Potentially active faults can be identified because the relationship between the orientation of active faults and the regional stress field is well known from basic principles of structural geology and rock mechanics. In other words, only faults of certain orientations are potentially activated during injection in a given area. The earthquakes apparently triggered by fluid injection at Guy, Ark., occurred on northeast trending, near-vertical faults, consistent with what would be expected from knowledge of the regional stress field and quite similar to the trend of active faults in the New Madrid Seismic Zone immediately to the east. Had these faults been identified during site characterization studies carried out as part of the permitting process, this site would not have been used for injection.



Wastewater from hydraulic fracturing is trucked away from drilling operations in Pennsylvania in the Marcellus Shale and moved elsewhere in the region where it will most likely be reinjected and reused.

Step 2: Minimize Pore Pressure Changes at Depth

Rocks in the upper part of Earth's crust contain pre-existing pore space, fractures and flaws. These void spaces are normally filled with freshwater near Earth's surface (in the upper 1 kilometer or so) and filled with saline brines at greater depths. Injecting fluids into the subsurface will increase the pressure in these voids, depending on the rate it is injected and the volume of pore space available to accommodate the injected fluids. It should be pointed out that injection always occurs at depths where the injected fluids are isolated from near-surface water supplies.

To minimize the potential for injection to trigger seismicity, it is obviously a good idea to minimize the pore pressure perturbations associated with injection. This can be accomplished in a variety of ways.

The best way, of course, is to minimize the injected volume of fluid. Consider the case of the disposal of flowback waters following hydraulic fracturing associated with shale gas development in the Marcellus Formation of the northeastern U.S. Typically, 25 to 50 percent of the water used during hydraulic fracturing flows back and needs to be disposed of. However, because it has been difficult to find suitable injection sites in this



Nearly all of the water used in hydraulic fracturing in the Marcellus Shale is reinjected during subsequent hydraulic fracturing operations. Meanwhile, it is stored in wastewater impoundment ponds like this one in Pennsylvania.

region (and quite expensive to haul water great distances to already operating injection wells), it is common practice to recycle flowback water by using it in subsequent hydraulic fracture operations rather than disposing of it in injection wells. In the Marcellus, nearly all of the water is recycled. That certainly minimizes the pore pressure perturbations.

Another way to reduce the pressure buildup associated with injection is to utilize highly permeable regional saline aquifers to dispose of wastewater. These aquifers can accommodate large volumes of injected fluids without experiencing significant pressure changes. The Ellenburger Formation in Texas is regionally extensive and highly permeable — one reason why many of the approximately 50,000 permitted wastewater disposal wells in the state have operated for so long, essentially without the occurrence of triggered seismicity. In cases where saline water is used for hydraulic fracturing, it is possible to reinject the water that flows back after fracturing into the same formations. When flowback water is injected into the

Operators and regulators should establish operational protocols — like perhaps a “traffic light” system — for wastewater injection sites located in areas where there is concern about the potential for triggered seismicity: Green means go, all systems working correctly; yellow means proceed with caution, seismicity detected; red means stop, seismicity potentially presents a hazard.

same saline aquifers from which the water used for hydraulic fracturing was produced, pressure in the aquifers decreases over time as more water is produced for hydraulic fracturing than injected following flowback.

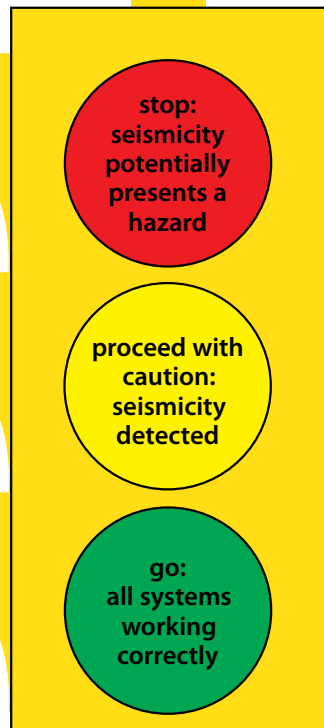
Alternatively, weak, poorly cemented and highly permeable sandstone formations would also be ideal for injection. Such formations deform plastically and do not store elastic strain energy that can be released in potentially damaging earthquakes. No earthquakes have been triggered in the 15 years during which a million metric tons per year of carbon dioxide from the Sleipner gas- and oilfield in the North Sea has been injected into the Utsira sand, a highly porous, regionally extensive saline aquifer.

In the same way that it’s important to plan for the possibility of triggered seismicity in advance, we have to be prepared to reduce injection rates, or even abandon wells if triggered seismicity cannot be stopped by limiting injection rates.

Obviously, cases will arise where well-cemented, less permeable and more brittle formations must be used for injection. In those cases, care must be taken to avoid large pore pressure changes. This can be done through modeling prior to injection once the permeability and capacity of the injection intervals have been determined. Well-established procedures have been developed over many decades by petroleum engineers to do this.

Step 3: Install Local Seismic Monitoring Arrays

Potentially active faults that might cause large and damaging earthquakes should be identifiable during the site characterization phase of permitting potential injection wells. Because smaller faults can escape detection, seismic monitoring



arrays should be deployed in the vicinity of injection wells when there is a cause for concern that injection might trigger seismicity.

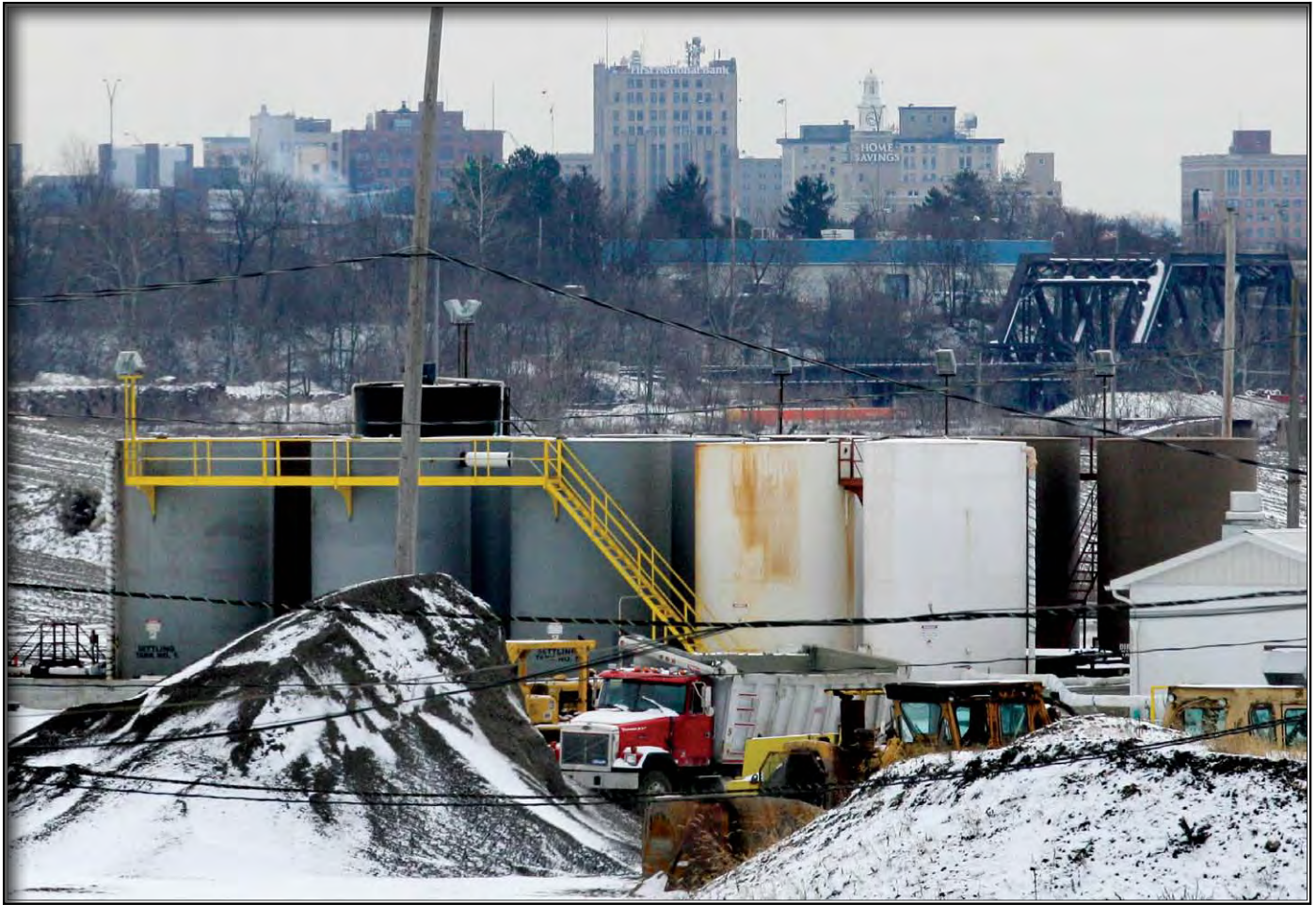
The locations and magnitudes of naturally occurring earthquakes are routinely determined on a real-time basis in numerous seismically active regions around the world. The instrumentation, data telemetry and analysis techniques used to accomplish this monitoring are well developed and easily implemented at relatively low cost. By supplementing regional networks with local seismic arrays near injection wells, accurate locations of earthquakes that might be triggered by injection can be used to determine the locations and orientations of the causative faults.

Although small faults cannot cause large earthquakes, even small earthquakes felt by the public will be a cause for concern and should be monitored.

Step 4: Establish Modification Protocols in Advance

Following precedents established to deal with earthquakes triggered during the development of enhanced geothermal systems, operators and regulators should jointly establish operational protocols for injection sites located in areas where there is concern about the potential for triggered seismicity. These protocols are sometimes referred to as “traffic light” systems.

Green means go: Once operational protocols and local seismic networks are in place and injection begins at agreed-upon rates, operators would have a green light to continue unless earthquakes begin to occur that appear to be



A saline wastewater injection well owned by Northstar Disposal Services LLC in Youngstown, Ohio. Following several small earthquakes in the area in December 2011, the company halted injection of wastewater into the well, which stopped the earthquakes. The wastewater is from the production of oil and gas.

related to injection. The occurrence of seismicity would be a cautionary yellow light. Once seismicity occurs, operators would slow injection rates and study the relationship between the seismicity and injection. Should seismicity cease, operations could potentially continue at reduced injection rates. In fact, it was demonstrated 40 years ago at Rangely that earthquakes could be turned on and off by modulating the injection rate and resultant increase in pore pressure at depth. With such protocols in place, the potential occurrence and associated response to triggered seismicity are pre-defined and known to all parties.

Step 5: Be Prepared to Alter Plans or Abandon Wells

In the same way that it's important to plan for the possibility of triggered seismicity in advance, we have to be prepared to reduce injection rates, or even abandon wells if triggered seismicity cannot be stopped by limiting injection rates.

That would be the red traffic light: Seismicity has been detected that appears to be associated with a fault potentially capable of producing a moderate-sized earthquake. In the case of the Arkansas triggered earthquakes, as well as a series of quakes thought to have been caused by wastewater injection in the Barnett Shale in Texas near the Dallas-Fort Worth metro area in 2008, the seismicity abated once injection in the problematic wells was terminated.

Overall, it is important for the public to recognize that the risks posed by injection of wastewater are extremely low. In addition, the risks can be minimized further through proper study and planning prior to injection, careful monitoring in areas where there is a possibility that seismicity might be triggered, and operators and regulators taking a proactive response if triggered seismicity were to occur.

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