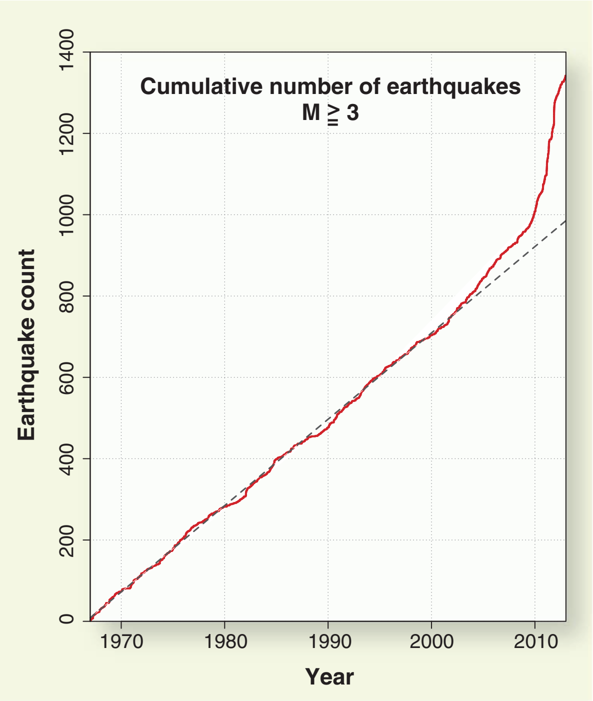
Injection-Induced Earthquakes

William L. Ellsworth

Background: Human-induced earthquakes have become an important topic of political and scientific discussion, owing to the concern that these events may be responsible for widespread damage and an overall increase in seismicity. It has long been known that impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids into underground formations are capable of inducing earthquakes. In particular, earthquakes caused by injection have become a focal point, as new drilling and well-completion technologies enable the extraction of oil and gas from previously unproductive formations.

Advances: Microearthquakes (that is, those with magnitudes below 2) are routinely produced as part of the hydraulic fracturing (or "fracking") process used to stimulate the production of oil, but the process as currently practiced appears to pose a low risk of inducing destructive earthquakes. More than 100,000 wells have been subjected to fracking in recent years, and the largest induced earthquake was magnitude 3.6, which is too small to pose a serious risk. Yet, wastewater disposal by injection into deep wells poses a higher risk, because this practice can induce larger earthquakes. For example, several of the largest earthquakes in the U.S. midcontinent in 2011 and 2012 may have been triggered by nearby disposal wells. The largest of these was a magnitude 5.6 event in central Oklahoma that destroyed 14 homes and injured two people. The mechanism responsible for inducing these events appears to be the well-understood process of weakening a preexisting fault by elevating the fluid pressure. However, only a small fraction of the more than 30,000 wastewater disposal wells appears to be problematic—typically those that dispose of very large volumes of water and/or communicate pressure perturbations directly into basement faults.

Outlook: Injection-induced earthquakes, such as those that struck in 2011, clearly contribute to the seismic hazard. Quantifying their contribution presents difficult challenges that will require new research into the physics of induced earthquakes and the potential for inducing large-magnitude events. The petroleum industry needs clear requirements for operation, regulators must have a solid scientific basis for those requirements, and the public needs assurance that the regulations are sufficient and are being followed. The current regulatory frameworks for wastewater disposal wells were designed to protect potable water sources from contamination and do not address seismic safety. One consequence is that both the quantity and timeliness of information on injection volumes and pressures reported to regulatory agencies are far from ideal for managing earthquake risk from injection activities. In addition, seismic monitoring capabilities in many of the areas in which wastewater injection activities have increased are not capable of detecting small earthquake activity that may presage larger seismic events.



Earthquakes with magnitude (M) ≥ 3 in the U.S. midcontinent, 1967–2012. After decades of a steady earthquake rate (average of 21 events/year), activity increased starting in 2001 and peaked at 188 earthquakes in 2011. Human-induced earthquakes are suspected to be partially responsible for the increase.

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ARTICLE OUTLINE

ADDITIONAL RESOURCES

The following resources provide an introduction to earthquake hazards and risk, the science of induced earthquakes, and strategies for managing the risk.

C. Nicholson, R. L. Wesson, "Earthquake hazard associated with deep well injection: A report to the U.S. Environmental Protection Agency," *U.S. Geol. Surv. Bull. 1951* (1990); http://pubs.usgs.gov/bul/1951/report.pdf.

Committee on Induced Seismicity Potential in Energy Technologies, *Induced Seismicity Potential in Energy Technologies* (National Research Council, Washington, DC, 2012); http://dels.nas.edu/Report/Induced-Seismicity-Potential-Energy-Technologies/13355.

S. Horton, Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake. *Seismol. Res. Lett.* **83**, 250–260 (2012). doi:10.1785/gssrl.83.2.250

Tutorial material on probabilistic seismic hazard analysis (PSHA): www.opensha.org/sites/opensha.org/files/PSHA_Primer_v2_0.pdf

M. D. Zoback, Managing the seismic risk posed by wastewater disposal. *Earth Magazine* **57**, 38–43 (2012).

Injection-Induced Earthquakes

William L. Ellsworth

Earthquakes in unusual locations have become an important topic of discussion in both North America and Europe, owing to the concern that industrial activity could cause damaging earthquakes. It has long been understood that earthquakes can be induced by impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids into underground formations. Injection-induced earthquakes have, in particular, become a focus of discussion as the application of hydraulic fracturing to tight shale formations is enabling the production of oil and gas from previously unproductive formations. Earthquakes can be induced as part of the process to stimulate the production from tight shale formations, or by disposal of wastewater associated with stimulation and production. Here, I review recent seismic activity that may be associated with industrial activity, with a focus on the disposal of wastewater by injection in deep wells; assess the scientific understanding of induced earthquakes; and discuss the key scientific challenges to be met for assessing this hazard.

Earthquakes are expected within tectonically active regions such as along plate boundaries or within distributed zones of deformation. Recent seismic activity across the coterminous United States, for example, concentrates along the plate boundaries of the West Coast and within the intermountain West (Fig. 1). Within such actively deforming zones, elastic strain energy accumulates in the crust, sometimes for centuries, before being released in earthquakes. The potential for earthquakes also exists within continental interiors, despite very low deformation rates (*1*). This is because shear stress levels within the interior of plates or near plate boundaries are commonly found to be near the strength limit of the crust (*2*). Under these conditions, small perturbations that effect fault stability can and do trigger earthquakes (*3*–*6*). For example, the injection of water under high pressure into impermeable basement rocks beneath Basel, Switzerland, to develop an enhanced geothermal system beneath the city induced four moment magnitude (M_w) 3 earthquakes in 2006 and 2007 (*7*) (earthquake magnitudes measured using other scales are denoted by M). These small earthquakes led to the abandonment of the project, loss of the investment, and ongoing litigation over compensation for damage. The extraction of natural gas from shallow deposits in the Netherlands also causes earthquakes (*8*). A recent M 3.4 event near Loppersum damaged scores of homes in the area, resulting in large losses for the property owners (*9*).

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Within the central and eastern United States, the earthquake count has increased dramatically over the past few years (Fig. 2). More than 300 earthquakes with $M \geq 3$ occurred in the 3 years from 2010 through 2012, compared with an average rate of 21 events/year observed from 1967 to 2000. States experiencing elevated levels of seismic activity included Arkansas, Colorado, New Mexico, Ohio, Oklahoma, Texas, and Virginia. The greatest rise in activity occurred in 2011 when 188 $M \geq 3$ earthquakes occurred. Although earthquake

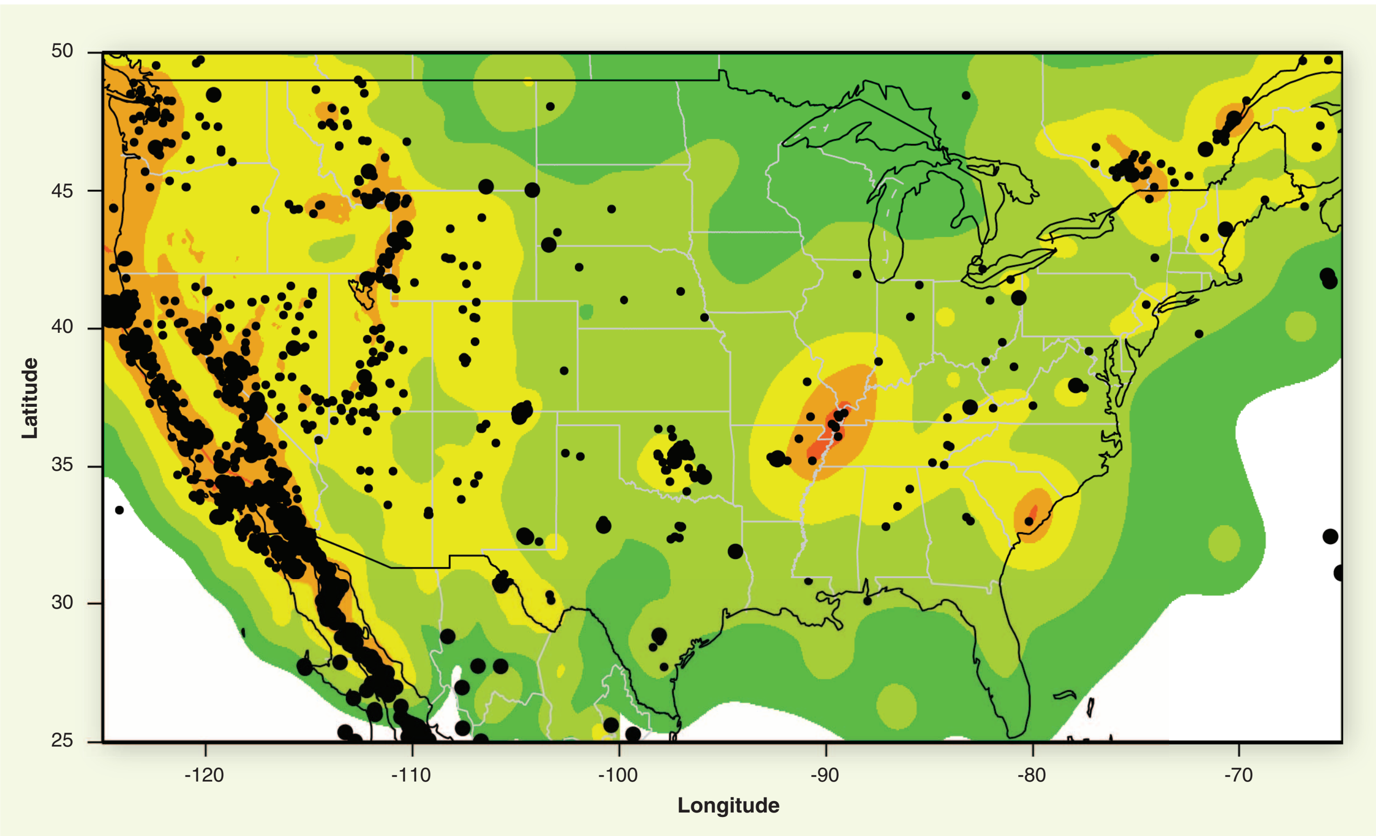

Fig. 1. Seismicity of the coterminous United States and surrounding regions, 2009–2012. Black dots denote seismic events. Only earthquakes with $M \geq 3$ are shown; larger symbols denote events with $M \geq 4$. Background colors give the probability of peak ground acceleration with a 2% probability of exceedance in 50 years, from the U.S. National Seismic Hazard Map (*1*). Red, ≥ 1*g*; orange, 0.3 to 1*g*; yellow, 0.1 to 0.3*g*; light green, 0.03 to 0.1*g*; darker green, 0.03 to 0.1*g*.

detection improved for $M < 3$ as the USArray transportable seismograph array began to pass through the region starting in 2008 (10), a recent report on seismicity in the central and eastern United States found that the probability of missing $M \geq 3$ earthquakes in the region has been near zero for decades (11). Consequently, the increased earthquake count represents a temporal change in earthquake rate. Because the hazard of damaging ground shaking is fundamentally related to the rate of earthquake occurrence (1), regions where the rate increased may be more hazardous than forecast by the 2008 version of the U.S. National Seismic Hazard Map (Fig. 1) (1). Understanding why seismicity increased and how this increase affects the hazard have become a priority for the earthquake-research community.

A number of these recent earthquakes occurred in areas where specific types of nearby industrial activities raise the possibility that these events were induced by human activity. Here, I will use the term "induced" to include both earthquakes triggered by anthropogenic causes that primarily release tectonic stress and those that primarily release stresses created by the industrial activity (4). Understanding which earthquakes may have been induced and, if so, how are challenging problems to solve in the current data-poor environment.

Several examples since 2011 highlight the difficulty in determining whether earthquakes were induced by human activity. The M_w 4.0 earthquake on 31 December 2011 in Youngstown, Ohio, appears to have been induced by injection of wastewater in a deep Underground Injection Control (UIC) class II well (12). The M_w 4.7 27 February 2011 central Arkansas earthquake has also been linked to deep injection of wastewater (13). The M_w 4.4 11 September 2011 earthquake near Snyder, Texas, occurred in an oil field where injection for secondary recovery has been inducing earthquakes for years (14). The M_w 4.8 10 October 2011 earthquake near Fashing, Texas, occurred in a region where long-term production of gas has been linked to earthquake activity (15). For others, such as the M_w 5.7 6 November 2011 central Oklahoma earthquake (16) or the M_w 4.9 17 May 2012 east Texas earthquake (17), where active wastewater-injection wells are located near their respective epicenters, the question of natural versus induced remains an active topic of research.

The potential association between deep wastewater disposal wells and earthquakes has received considerable attention due to the association of this activity with the development of tight shale formations for gas and petroleum by hydraulic fracturing, or "fracking" (5). Wells used in the U.S. petroleum industry to inject fluids are regulated as UIC class II wells. Approximately 110,000 of these wells are used for enhanced oil recovery. In addition, 30,000 class II wells in the United States are used for wastewater disposal. Of these wells, most have no detected seismicity within tens of kilometers, although a few are correlated with seismicity (18). However, this can be said with confidence only for earthquakes $M_w \geq 3$, as smaller earthquakes are not routinely reported in the central and eastern United States. So it is possible that smaller earthquakes could be more common in the vicinity of these wells. In California, where the completeness threshold is below M_w 2, the majority of the 2300 active wastewater-injection wells are located in regions of low seismicity. As with elsewhere in the United States, a small fraction of the California wastewater wells coincide with earthquakes, which raises the question of what factors distinguish those seismically active wells from the majority of wells if the earthquakes and injection activities are related.

Mechanics of Induced Earthquakes

Earthquakes release stored elastic strain energy when a fault slips. A fault will remain locked as long as the applied shear stress is less than the strength of the contact. The failure condition to initiate rupture is usually expressed in terms of the effective stress $\tau_{crit} = \mu(\sigma_n - P) + \tau_o$, where the critical shear stress τ_{crit} equals the product of the coefficient of friction μ and the effective normal stress given by the difference between the applied normal stress σ_n and the pore pressure P (3, 19, 20). For almost all rock types, μ lies between 0.6 and 1.0, and the cohesive strength of the sliding surface, τ_o, is negligible under typical crustal conditions. Increasing the shear stress, reducing the normal stress, and/or elevating the pore pressure can bring the fault to failure, triggering the nucleation of the earthquake (Fig. 3). Once initiated, sliding resistance drops and seismic waves radiate away, driven by the imbalance between the elastic stress stored in the surrounding rock mass and the frictional resistance of the dynamically weakened sliding surface. Rupture will continue to propagate, as long as the wave-mediated stress at the rupture front exceeds the static strength, and may extend into regions where the ambient stresses are below the failure threshold.

Rocks fail in tension when the pore pressure exceeds the sum of the least principal stress, σ_3, and the tensile strength of the rock, forming an opening-mode fracture that propagates in the plane normal to σ_3. The industrial process of hydraulic fracturing commonly involves both tensile and shear failure. Depending on the local stress state, hydraulically conductive fractures may be induced to fail in shear before $P = \sigma_3$. A successful "frac job" may create a fracture network dominated by pathways created by shear failure (21).

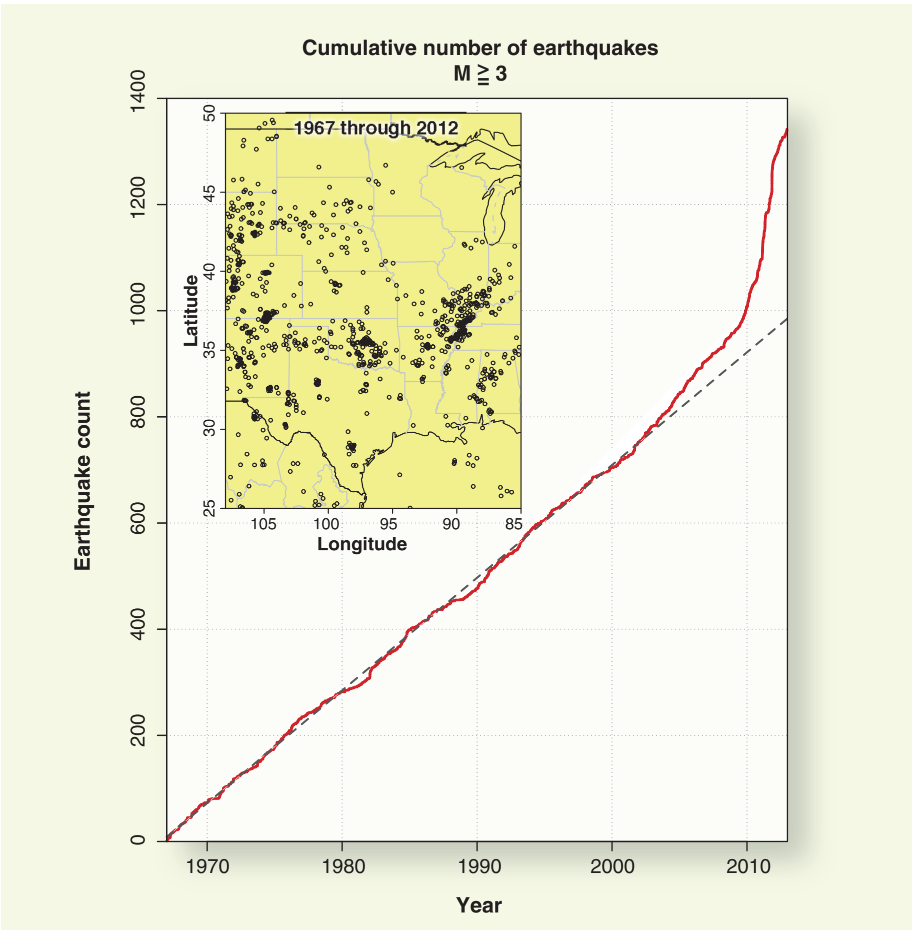

Fig. 2. Cumulative count of earthquakes with $M \geq 3$ in the central and eastern United States, 1967–2012. The dashed line corresponds to the long-term rate of 21.2 earthquakes/year. (**Inset**) Distribution of epicenters in the region considered here.

Earthquakes are known to be induced by a wide range of human activities (3–5) that modify the stress and/or pore pressure (Fig. 3). At present, with the use of seismological methods, it is not possible to discriminate between man-made and natural tectonic earthquakes. Induced earthquakes sometimes occur at the source of the stress or pressure perturbation; at other times, these events take place deep below and kilometers away from the source. When removed from the source, induced earthquakes typically release stored tectonic stress on preexisting faults, as do natural earthquakes. Sometimes induced events occur shortly after the industrial activity begins, but in other cases they happen long after it has been under way or even ceased. Factors that should enhance the probability of a particular stress or pore-pressure perturbation inducing earthquakes include the magnitude of the perturbation, its spatial extent, ambient stress condition close to the failure condition, and the presence of faults well oriented for failure in the tectonic stress field. Hydraulic connection between the injection zone and faults in the basement may also favor inducing earthquakes, as the tectonic shear stress increases with depth in the brittle crust (2). In addition, the larger the fault, the larger the magnitude of earthquakes it can host.

Methods for anticipating the time of failure have long been the "holy grail" of seismology (22). Though short-term prediction remains an elusive goal, it has been proposed that critically loaded faults have enhanced triggering susceptibility to dynamic stresses from distant earthquakes (23). Specifically, some but not all of the sites where fluid-injection–induced earthquakes are suspected of contributing to the recent increase in seismicity in the midcontinent (Fig. 2) experienced increased rates of microearthquakes in the days immediately after three recent great earthquakes (23).

Earthquakes Induced by Hydraulic Fracturing

The industrial process of hydraulic fracturing involves the controlled injection of fluid under pressure to create tensile fractures, thereby increasing the permeability of rock formations. It has been used for well over half a century to stimulate the recovery of hydrocarbons. For many decades, the primary application was to improve the output of aging oil and gas reservoirs. Beginning in the late 1990s, technologies for extracting natural gas and oil from tight shale formations led to the development of new natural gas fields in many parts of the central and eastern United States, western Canada, and Europe. Global development of oil and gas from shale will undoubtedly continue, as the resource potential is high in many parts of the world.

Extracting hydrocarbons from shale requires the creation of a network of open fractures connected to the borehole. Horizontal drill holes extending up to several kilometers within the shale formation undergo a staged series of hydraulic fractures, commonly pressurizing a limited section of the cased well at a time to stimulate the flow of gas or oil into the well. Each stage involves the high-pressure injection of water into the formation. Fracking intentionally induces numerous microearthquakes, the vast majority with $M_w < 1$.

Several cases have recently been reported in which earthquakes large enough to be felt but too small to cause structural damage were associated directly with fracking. These cases are notable because of the public concern that they raised, despite maximum magnitudes far too small to cause structural damage. Investigation of a sequence of felt events with maximum M 2.9 in south central Oklahoma revealed a clear temporal correlation between fracking operations in a nearby well and the seismic activity (24). Available data were insufficient to definitely rule out a natural cause due to the occurrence of some natural seismicity in the general area. In April and May 2012, a series of induced earthquakes with maximum M 2.3 occurred near Blackpool, United Kingdom (25), during fracking to develop a shale gas reservoir.

One of the major shale plays in the United States—the Marcellus Shale of the Appalachian Basin in Pennsylvania, West Virginia, Ohio, and New York—lies within a region characterized by low levels of natural seismic activity (Fig. 1). The regional seismographic network operated by Lamont Doherty Earth Observatory (LDEO) systematically catalogs all earthquakes with $M \geq 2$ in Pennsylvania (Fig. 4). Although thousands of hydraulic fractures were done in Pennsylvania since major development of the field began in 2005, only six earthquakes with $M \geq 2$ were detected by the LDEO network within the footprint of the Marcellus Shale, the largest of which was just M 2.3. The largest earthquake in the region since the development of shale gas happened across the Ohio border in Youngstown, where it was induced by injection (12), much of the fluid apparently coming from wells in Pennsylvania.

Beginning in 2009, an unusual sequence of earthquakes was noted in the Horn River Basin of British Columbia, including 21 events with M_w 3.0 and larger. Only the largest, at M_w 3.6, was reported as felt by workers in this remote area where it did no damage (26). The investigation into the cause of these events by the BC Oil and Gas Commission (26) concluded that the events "were caused by fluid injection during hydraulic fracturing in proximity of pre-existing faults." Two of the hydrofrac treatments were recorded by dense seismometer deployments at the surface. Precise hypocentral locations showed that the induced earthquakes occurred on previously unknown faults located outside of the stimulation interval that were well oriented for failure in the ambient stress field. Apparently, fracture pressure was quickly communicated through hydraulically conductive pathways and induced slip on critically stressed faults via reduction of the effective normal stress.

Earthquakes Induced by Deep Injection

There has been a growing realization that the principal seismic hazard from injection-induced earthquakes comes from those associated with disposal of wastewater into deep strata or basement formations (5). Before 2011, the M_w 4.8 event on 9 August 1967 near Denver, Colorado, was the largest event widely accepted in the scientific community as having been induced by wastewater injection (5). The hazard landscape of what is possible has shifted due to the role that wastewater injection into a depleted oil field may have played in the M_w 5.7 6 November 2011 central Oklahoma earthquake (16), although a consensus on its origin has not yet been reached (27). This earthquake damaged homes and unreinforced masonry buildings in the epicentral

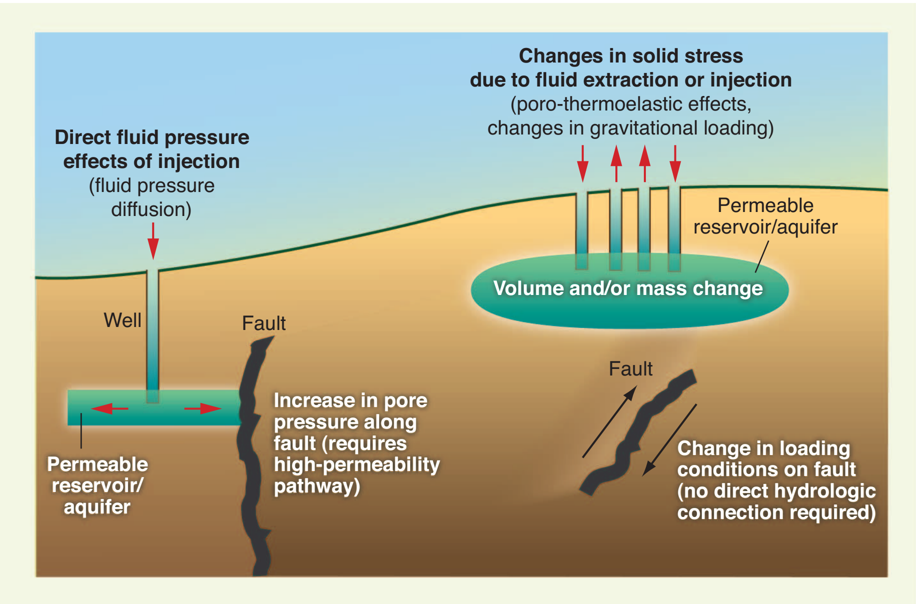

Fig. 3. Schematic diagram of mechanisms for inducing earthquakes. Earthquakes may be induced by increasing the pore pressure acting on a fault (**left**) or by changing the shear and normal stress acting on the fault (**right**). See (4).

area and was felt as far as 1000 km away in Chicago, Illinois.

The November 2011 central Oklahoma earthquake sequence initiated very close to a pair of wastewater-injection wells where disposal operation began 18 years earlier (*16*). No unusual seismicity was detected in this historically quiet region, where only a few events of $M < 2$ were noted, until a M_w 4.1 earthquake occurred near the wells in early 2010. Aftershocks of this event continued sporadically through 2010 and into mid-2011. This decaying sequence was shattered by a M_w 5.0 earthquake on 5 November 2011, followed 20 hours later by the M_w 5.7 mainshock. With the initiating point of the November sequence within 1.5 km of the injection wells and some earthquake hypocenters at the same depth as injection, the potential for a causal connection between injection and the earthquakes is clear. The long delay between the start of injection and the earthquakes, however, deviates from the pattern seen in other documented cases of injection-induced seismicity, such as the 2011 Youngstown, Ohio, earthquake where there was, at most, a few months of delay before induced seismicity began. In the Oklahoma case, years of injection may have been needed to raise the pore pressure above the preproduction level in this depleted oil field before fault strength was exceeded (*16*).

Much of the concern about earthquakes and fracking centers on the injection of wastewater, composed of flowback fluids and coproduced formation brine in deep wells, and not on fracking itself. Wastewater disposal appears to have induced both the 2011 central Arkansas earthquake (*13*) and the 2011 Youngstown, Ohio, earthquake (*12*), as mentioned above. Unprecedented levels of seismicity have also been seen in the Barnett Shale in north central Texas, where commercial development of shale gas was pioneered. Since development began in late 1998, nine earthquakes of $M \geq 3$ occurred, compared with none in the preceding 25 years. A notable sequence occurred in the Dallas–Fort Worth area from October 2008 through May 2009. A detailed investigation of this sequence concluded that the earthquakes were most probably caused by disposal of shale gas wastewater in a UIC class II disposal well at the Dallas/Fort Worth International Airport (*28*), although as with the Oklahoma earthquake, not all investigators agree that the case is proven (*29*). Because routine earthquake reporting in the region is incomplete for events of $M < 3$, the passage of the USArray Transportable Array through the region over an 18 month period in 2009–2011 made it possible to improve magnitude completeness to M 1.5 and location accuracy by several fold. Epicenters for the most reliable locations were clustered in eight groups, all within 3 km of high-rate (>25,000 m^3/month) wastewater-injection wells (*18*). These results suggest that the injection rate, as well as the total volume of injection, may be a predictor of seismic potential.

Lessons from Three Case Studies of Deep, High-Volume Injection

Conclusions about the cause of many of the recent earthquakes suspected of being induced by injection are complicated by incomplete information on the hydrogeology, the initial state of stress and pore pressure, the pumping history of the well(s), and where pressure changes are being communicated at depth. Routine earthquake locations with uncertainties of 5 to 10 km and a high magnitude-detection threshold are of limited use. Three particularly well-documented cases of injection-induced seismicity from Colorado illustrate what can be learned when more is known about the pre-injection stress state and seismicity, as well as the injection history.

Rocky Mountain Arsenal

In 1961, a deep injection well was drilled at the Rocky Mountain Arsenal (RMA) northeast of Denver, Colorado, to dispose of hazardous chemicals produced at this defense plant (*30*). Within several months of the start of routine injection in the 3.6-km-deep well in March 1962, residents of the northeastern Denver area began to report earthquakes, and events registered on two nearby seismic stations. Between the start of injection and its termination in February 1966, a total of 13 earthquakes with body wave magnitudes (m_b) 4 and larger occurred. The following year, the three largest of the Denver earthquakes occurred, including the M_w 4.8 event on 9 August 1967 that caused minor structural damage near the epicenter. By this time, the earthquakes had migrated as far as 10 km from the injection point (*31*). Hydrologic modeling showed that the migrating seismicity would track a critical pressure front of 3.2 MPa (*32*). Although declining, earthquake activity continued for the next two decades, including a m_b 4.3 earthquake on 2 April 1981. The RMA earthquakes demonstrate how the diffusion of pore pressure within an ancient fault system can initiate earthquakes many kilometers from the injection point, delayed by months or even years after injection ceased.

Rangely

The insights gained from RMA led to the suggestion that earthquakes could be controlled by modulating the fluid pressure in the fault, according to the effective-stress relation (*19*). In 1969, the U.S. Geological Survey (USGS) began an experiment to test the effective-stress hypothesis in the Rangely oil field in northwestern Colorado (*20*). Water injected into the reservoir under high pressure had been used to enhance oil production at Rangely since 1957. The operator, Chevron Oil Company, gave USGS permission to regulate the fluid pressure in a portion of the field that was known to be seismically active. Laboratory measurements of the coefficient of friction on core samples of the reservoir rocks and in situ determination of the state of stress led to the prediction that a critical fluid pressure of 25.7 MPa would be required to induce earthquakes. Two cycles of fluid injection and withdrawal were conducted between 1969 and 1973. When the pressure in a monitoring well exceeded the target pressure, earthquake activity increased; when pressure was below the threshold, earthquake activity decreased. In particular, the earthquake activity ceased within 1 day of the start of backflow in May 1973, providing strong evidence that the rate of seismicity could be controlled by adjusting the pore pressure at the depth where earthquakes initiate, if stress conditions and the strength of the faulted rock mass were known. The rapid response of seismicity at the onset of backflow also emphasized the importance of understanding the geohydrology and, in particular, the importance of hydraulically conductive faults and fractures for transmitting pore pressure within the system.

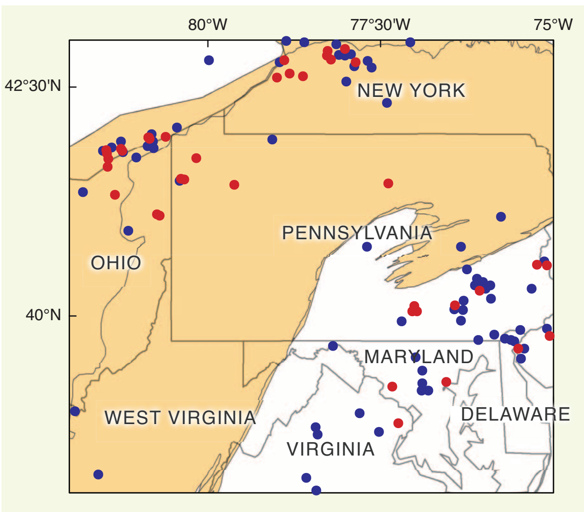

Fig. 4. Seismicity of Pennsylvania and surrounding regions, 1970–2012. Shading indicates areas underlain by deposits of the Marcellus Shale. Blue dots, earthquakes before 2005; red dots, after 2005. Seismicity was determined by the Lamont Doherty Earth Observatory (*45*).

Paradox Valley

An ongoing fluid-injection project has been under way since 1996 in Paradox Valley in southwestern Colorado, where the saline shallow water table is being suppressed by pumping to prevent salt from entering the Dolores River as it crossed the valley and, eventually, the Colorado River further downstream (*33*). In its natural state, the Dolores River picks up salt from the groundwater as it crosses Paradox Valley. After extensive study of alternatives, the U.S. Bureau of Reclamation determined that high-pressure injection of brine into a deep disposal well (UIC class V) provided the best method for reducing the salinity of the Dolores River. Injection occurs in a tight, but highly fractured dolomitic limestone with a fracture-dominated porosity of less than 6% located 4.3 km below land surface. To date, more than 7×10^6 m^3 of brine have been injected. One operational objective, based on both the RMA and Rangely experiences, was the need to minimize the magnitude of earthquakes induced by injection.

A local seismic network was established in 1985 to determine background levels of seismicity before the drilling of the well and initial injection tests. Between 1985 and June 1996, only three tectonic earthquakes were detected within 15 km of the well and just 12 within 35 km (*33*). However, hundreds of earthquakes were induced during injection tests conducted between 1991 and 1995. Most of these earthquakes were concentrated within 1 km of the injection point, although a few were located 3 to 4 km from this site. All events were below *M* 3. The occurrence of induced earthquakes is not notable here, as injection required a bottom hole pressure in excess of the hydraulic fracture pressure of 70 MPa.

High injection pressure was needed to keep pace with the disposal requirements; consequently, induced earthquakes were expected when disposal operations went into production in 1996. Continuous monitoring of injection pressures and volumes, along with seismicity, is being conducted to insure the safe operation of the project. During the first few years of operations, several of the induced earthquakes exceeded *M* 3, necessitating changes in injection procedures in an attempt to limit the maximum magnitude. The dimension of the activated zone also grew, with earthquakes as far as 8 km from the injection point appearing within a year and events to beyond 12 km several years later (Fig. 5). Because seismicity rapidly abated after each injection test, it was hypothesized that occasional shutdowns of 20 days would allow the fluid pressure to equilibrate, reducing the potential for larger events (*33*). By itself, this procedure proved inadequate, as a *M* 4.3 event was induced in May 2000.

After this earthquake, a new procedure was introduced in 2000 that involved periodic 20-day shutdowns and a 33% reduction in the injection volume, which initially reduced the required bottom hole pressure to 78 MPa. Over the following decade, the pressure required to inject that volume steadily increased to more than 84 MPa in 2012, drawing the revised strategy into question, as a steadily increasing injection pressure is not sustainable in the long term. On 24 January

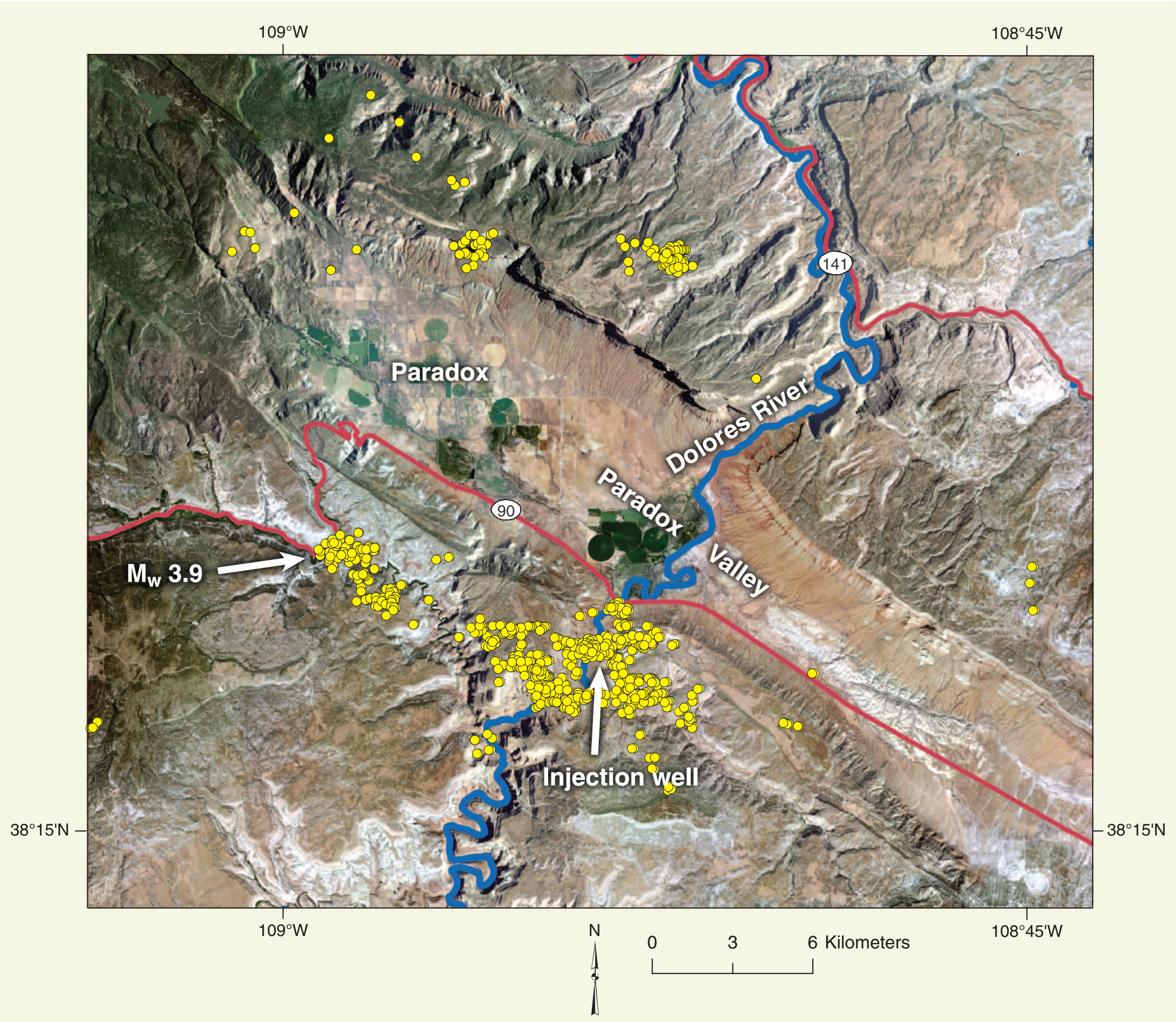

Fig. 5. Seismicity near Paradox Valley, Colorado. The U.S. Bureau of Reclamation extracts saline groundwater from shallow wells where the Dolores River crosses Paradox Valley to prevent its entry into the Colorado River system. Since 1996, the brine has been disposed of by injection into a 4.3-km-deep UIC class V well. Injection has induced more than 1500 earthquakes with $M \geq 1$, including the M_w 3.9 earthquake on 25 January 2013, which was located 8 km northwest of the well.

2013, a M_w 3.9 earthquake occurred 8 km northwest of the well in a previously active cluster, causing strong shaking in the town of Paradox, Colorado (Fig. 5). As a consequence, injection was halted for 12 weeks before restarting at a reduced rate. The Paradox Valley experience illustrates how long-term, high-volume injection can lead to the continued expansion of the seismically activated region and the triggering of large-magnitude events many kilometers from the injection well more than 15 years after observation of the initial seismic response. This case study also illustrates the challenges for managing the risk once seismicity has been induced.

Other Causes of Induced Earthquakes

According to the effective-stress model described above, earthquakes can be induced by either reducing the effective normal stress or raising the shear stress (*3*–*5*). It has been known for decades that large reservoirs can induce earthquakes either from the effect of the elastic load of the reservoir or by diffusion of elevated pore pressure (*34*). Well-known examples include the deadly 1967 *M* 6.3 earthquake in Koyna, India (*35*). Yet, establishing a causal connection can be difficult when natural seismicity occurs nearby. For example, the debate about the role of the Zipingpu reservoir in triggering the M_w 7.9 2005 Wenchuan, China, earthquake may never be resolved (*36*, *37*). What is clear, however, is that deep reservoirs in tectonically active zones carry a real risk of inducing damaging earthquakes.

Earthquakes throughout the world are also recognized to be associated with mining, petroleum and gas production, and geothermal energy extraction. Withdrawal of large volumes of fluid or gas from a reservoir or creation of a void space in a mine may modify the state of stress sufficiently to induce earthquakes that relax the stress perturbations (*4*). Production may also release tectonic stress. The long-term pumping of groundwater may have induced the deadly M_w 5.1 earthquake in Lorca, Spain, on 11 May 2011 (*38*). Pore-pressure changes alone can also induce seismicity, such as by waterflooding for secondary recovery of oil or to maintain the fluid level in a geothermal reservoir, or when a mine is abandoned and allowed to flood (*3*, *4*). The physical connection between operational parameters such as injected volume and the seismic response can be complex. In the Salton Sea Geothermal Field, for example, the seismicity rate positively correlates with the net volume of produced fluid (extraction minus injection) rather than net injection, as would be expected if seismicity rate simply tracked pore pressure (*39*). This underscores the importance of geomechanical modeling for transferring understandings developed in one setting to others.

Hazard and Risk of Induced Earthquakes

The hazard from earthquakes depends on proximity to potential earthquake sources, their magnitudes, and rates of occurrence and is usually expressed in probabilistic terms (*1*, *40*). The U.S. National Seismic Hazard Map, for example, gives the exceedance probabilities for a variety of ground-motion measures from which the seismic design provisions in the building codes are derived (Fig. 1) (*1*). Our understanding of the hazard will evolve as new information becomes available about the underlying earthquake sources, which are ideally derived from a combination of fault-based information and historical seismicity. Accounting for the hazard of induced earthquakes, however, presents some formidable challenges.

In the current U.S. map (Fig. 1), for example, the estimated hazard in most parts of the central and eastern regions of the country derives exclusively from historical seismicity. How should increases in the earthquake rate since 2009 (Fig. 2) be incorporated in the model? Should identified or suspected induced earthquakes be treated the same as or differently than natural events? In particular, do induced earthquakes follow the same magnitude-frequency distribution models as natural earthquakes? This issue has particular importance, as the high end of the magnitude distribution, where events are infrequent, contributes disproportionately to both the hazard and risk. Although injection-induced earthquakes have done only minor damage in the United States to date (*5*), the 2011 central Oklahoma earthquake was the same magnitude as the 1986 San Salvador, El Salvador, tectonic earthquake that killed more than 1500 people, injured more than 10,000, and left 100,000 homeless (*41*). Losses on this scale are unlikely in North America and northern Europe, where a catastrophic building collapse in a M_w 5.7 earthquake is unlikely, but the same cannot be said for large portions of the world where nonductile concrete frame or unreinforced masonry buildings are prevalent. The earthquake that killed nine and caused serious damaged Lorca, Spain, was even smaller at M_w 5.1 (*40*). The heavy losses in this possibly induced earthquake resulted from the exposure of many fragile buildings to strong shaking from this very shallow-focus earthquake (*42*). This event should serve as a reminder that risk is the product of the hazard, exposure, and vulnerability.

Unknown Knowns

Ignorance of the things that we understand we should know but do not leaves us vulnerable to unintended consequences of our actions. The effective-stress model provides straightforward guidance for avoiding induced earthquakes but requires knowledge that we rarely possess of the stress state and pore pressure acting on the fault. Quantitative predictions from the model depend on knowing initial stress and pore-pressure conditions and how perturbations to those conditions due to injection will affect the surroundings. For example, pore-pressure changes in a fault kilometers from the injection point depend on the hydrologic characteristics of connecting pathways that will, in all likelihood, be poorly known. The seismic response might not take place immediately, and decades may elapse before a damaging event occurs, as illustrated by the recent Paradox Valley earthquake and possibly the central Oklahoma earthquake as well. Simply injecting water by gravity feed (pouring it down the well with no surface pressure) sounds safe enough. But if the deep aquifer system was originally underpressured and the faults were in frictional equilibrium with the stress (*2*), this apparently benign type of injection can bring faults to failure by raising the water table and, hence, the pore pressure acting on the faults.

The fact that the great majority of UIC class II injection wells in the United States appear to be aseismic, at least for earthquakes $M_w > 3$, suggests that ambient conditions in geologic formations commonly approved for disposal are far enough removed from failure that injection can be done with low risk, provided that the pressure perturbation remains confined within the intended formation. The largest injection-induced events have all involved faulting that is considerably deeper than the injection interval (*13*, *16*, *30*, *43*), suggesting that transmission of increased pressure into the basement elevates the potential for inducing earthquakes. Consequently, detection of seismicity in the vicinity of the well or changes in seismicity in the neighborhood should prompt reevaluation of the hazard.

License and operational requirements for UIC class II wells in the United States are regulated under the Safe Drinking Water Act, by the U.S. Environmental Protection Agency or by delegation of authority to state agencies. The law's provisions are primarily directed toward protection of potable aquifers by requiring injection into formations deep below and geologically isolated from drinking water sources. As such, the law focuses on well integrity, protection of impermeable barriers above the injection zone, and setting operational injection pressure limits to avoid hydraulically fracturing the well. Diffusion of pore pressure into basement faults or injection pressure that would raise critically stressed faults to failure is not considered in U.S. federal regulations. From a scientific standpoint, measuring the initial stress state and pore pressure, tracking of injection history, and careful seismic monitoring would be of great value. At present, little more is required by regulation than an estimate of the fracture pressure (not to be exceeded) and monthly reporting of total injection volume and average injection pressure. In most cases, this information is not sufficient to apply the effective-stress model or gain an understanding of the hazard posed by injection activity.

Reducing the Risk of Injection-Induced Earthquakes

How can the risk of inducing damaging earthquakes through human activity be minimized in an information-poor environment? Long-term and high-volume injection in deep wells clearly carries some risk (*18*), even though most wells are apparently aseismic (*5*). In contrast, earthquakes induced during hydraulic fracturing have lower risk because of their much smaller magnitudes. The largest fracking-induced earthquakes

(*24*, *26*) have all been below the damage threshold for modern building codes.

One approach for managing the risk of injection-induced earthquakes involves setting seismic activity thresholds that prompt a reduction in injection rate or pressure or, if seismic activity increases, further suspension of injection (*44*). Such "traffic-light" systems have been used selectively, going back to at least the RMA well pump tests in 1966–1967. The traffic-light system used in in Basel, Switzerland (*7*), did not stop the four M_w 3 earthquakes from happening but might have prevented larger events. The decision to stop injection in the Youngstown, Ohio, well, based on the seismicity (*12*) and made the day before the M_w 4.0 event, resulted in seismicity near the well declining within a month. All of these examples feature better seismic monitoring capabilities than currently exist in much of the United States or most of the rest of the world. Lowering the magnitude-detection threshold in regions where injection wells are concentrated to below M_w 2 would certainly help, as a traffic-light system using the current U.S. detection threshold of M_w 3 in many of these areas would have limited value. Improvements in the collection and timeliness of reporting of injection data to regulatory agencies would provide much-needed information on hydrologic conditions potentially associated with induced seismicity. In particular, daily reporting of volumes, peak, and mean injection pressures would be a step in the right direction, as would measurement of the pre-injection formation pressure.

Ultimately, better knowledge of the stress and pressure conditions at depth; the hydrogeolgic framework, including the presence and geometry of faults; and the location and mechanisms of natural seismicity at a few sites will be needed to develop a predictive understanding of the hazard posed by induced earthquakes. Industry, regulatory agencies, and the public are all aware that earthquakes can be induced by fluid injection. Industry needs clear requirements under which to operate, regulators must have a firm scientific foundation for those requirements, and the public needs assurance that the regulations are adequate and are being observed.

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