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Induced Seismicity: The Potential for Triggered Earthquakes in Kansas

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Introduction

Earthquake activity in the Earth's crust is known as seismicity. When linked to human activities, it is commonly referred to as "induced seismicity." Industries that have been associated with induced seismicity include oil and gas production, mining, geothermal energy production, construction, underground nuclear testing, and impoundment of large reservoirs (National Research Council, 2012). Nearly all instances of induced seismicity are not felt on the surface and do not cause damage.

In the early 2000s, concern began to grow over an increase in the number of earthquakes in the vicinity of a few oil and gas exploration and production operations, particularly in Oklahoma, Arkansas, Ohio, Colorado, and Texas. **Horizontal drilling** in conjunction with **hydraulic fracturing** has often been singled out for blame in the public discourse. Hydraulic fracturing, popularly called "fracking," does cause extremely low-level seismicity, too small to be felt, as do explosions associated with quarrying, mining, dam building, and other industrial activities. Although the actual process of hydraulic fracturing has been suspected of inducing larger earthquakes a few times worldwide, the U.S. Geological Survey has found no evidence to suggest that it has contributed much to increases in the rate of earthquakes (Hayes, 2012).

Felt earthquakes associated with any oil and gas production activities are rare. In the United States, only a small fraction of the hundreds of thousands of wells currently in operation have been suspected of inducing earthquakes large enough to be felt or cause damage (National Research Council, 2012). Most often, detected seismic activity associated with oil and gas operations is thought to be triggered when wastewater is injected into a disposal well. In the disposal process, waste products—such as saltwater produced with oil and gas and recovered hydraulic fracturing fluids—are injected into deep and confined porous rock.

Terms in **bold** *are defined in the glossary.*

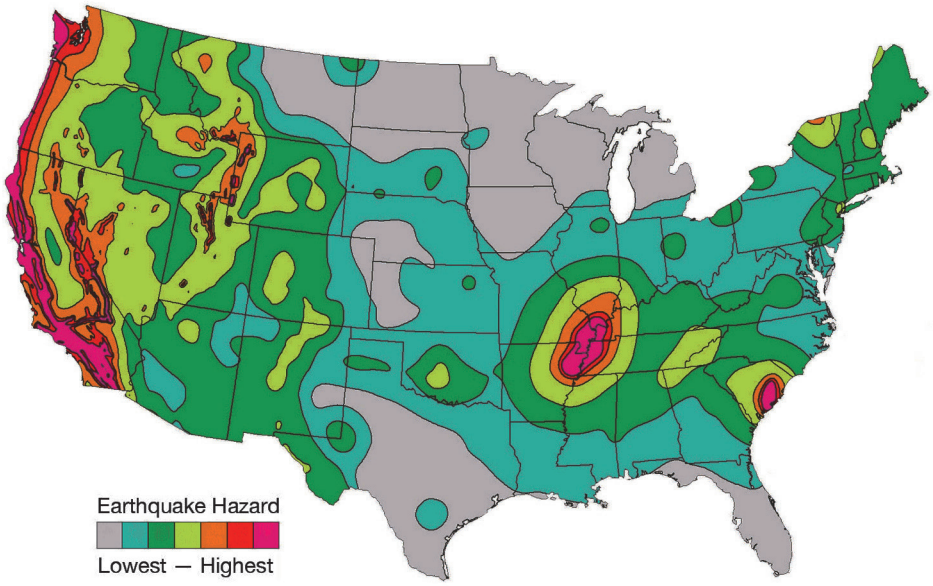

Figure 1—Earthquake hazard maps show the probability that ground shaking, or motion, will exceed a certain level, over a 50-year period. The low-hazard areas on this map have a 2% chance of exceeding a low level of shaking and the high-hazard areas have a 2% chance of topping a much greater level of shaking (modified from USGS, 2008).

Identifying a link between earthquakes and human activities is difficult. Complex subsurface geology and limited data about that geology make it hard to pinpoint the cause of many seismic events in the midcontinent, particularly in regions historically prone to naturally occurring low-level seismic activity. In south-central Kansas, for example, several small earthquakes have been recorded near disposal wells starting in September 2013, about three years after horizontal drilling activities in the **Mississippian limestone play**—and associated water disposal—had crossed over the state line into Kansas from Oklahoma. However, the region also experienced several small historical earthquakes long before the increased oil activity, making it difficult to determine the cause of the recent seismic events. Although some areas of Kansas are at greater risk of seismicity than others, whether natural or induced, none of the state is in a high-hazard earthquake zone (fig. 1).

Scientists continue to monitor and evaluate possible instances of induced seismicity. In states with significant increases in seismic activity, including Oklahoma, monitoring has increased in localized areas where unusually high rates of seismicity have occurred near oil and gas production activities. To

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help reduce the potential for induced seismicity related to the rate of injection of wastewater into disposal wells, scientists and others have developed some best-practice recommendations that would help prevent activation of stressed faults.

Natural vs. Induced Seismicity

Most seismic activity occurs when stress within the Earth's crust causes a fault or faults in subsurface rocks to slip and release enough energy to generate tremors. The vast majority of earthquakes are instigated naturally and generally happen where the Earth's **tectonic plates** interact. For the United States, that means most seismic activity is on the west coast along the boundary between the Pacific and North American plates.

Away from plate boundaries, earthquakes are most often triggered when geological processes, such as the deposition and erosion of surface rock, alter the balance of opposing stresses on subsurface rocks. Change in stress increases or decreases strain—the amount of rock deformation brought about by stress—which weakens the stability of faults confined by the stress. Faults may then slip and release pent-up energy, which rolls in waves through the Earth's crust (Ellsworth, 2013).

The U.S. Geological Survey estimates several million earthquakes occur around the world each year, although many small ones go undetected (USGS, 2014). Seismic events too small to be felt on the surface are known as microearthquakes, or microseisms.

The term "induced seismicity" is popularly used for any seismic activity linked to human activity. Some researchers, however, more narrowly define "induced seismicity" as seismicity caused solely by human activity and use the term "triggered seismicity" to define human activity that sets off a small transient event, which then instigates or contributes to a larger earthquake controlled by natural stresses (Cesca, 2012). Because the amount of influence a human activity has on a seismic event is hard to establish, that distinction is not always made. "Induced seismicity" is used throughout this circular to refer to any seismic event influenced by human activities.

Measuring Earthquake Magnitude and Intensity

Earthquakes can be measured in two different ways. One method is based on magnitude—the amount of energy released at the earthquake source. The other is based on intensity—how much the ground shakes at a specific location. Although several scales have been developed over the years, the two commonly used today in the United States are the Modified Mercalli scale, which measures intensity, and the moment magnitude scale, which measures magnitude (M), or size. The moment magnitude scale is now preferred to the older, more familiar Richter scale because it overcomes some of the limitations of the Richter scale (USGS, 2014).

Measurements on the moment magnitude scale are determined using a complex mathematical formula to convert motion recorded with a **seismometer** into a number that represents the amount of energy released during an earthquake. Energy released for each whole number measurement is about 31 times greater than that released by the whole number before (USGS, 2014). The smallest earthquakes recorded today have negative magnitudes (e.g., M -2.0) on the moment magnitude scale because the scale's range is based on that of the Richter scale, developed in the 1930s when monitoring equipment was less sensitive. Scientists are now able to detect earthquakes smaller in magnitude than the "0" used as the Richter scale baseline.

Measurements of intensity on the Modified Mercalli scale range from I to XII and are based solely on damage assessment and eyewitness accounts. Intensity measurements near the source of an earthquake are generally higher than those at a distance. They can also remain high in the direction the waves of energy travel and may be magnified in areas underlain by loose gravels and unconsolidated sediments. Determining intensity can be difficult in sparsely populated areas with few buildings because intensity is calculated largely on the effects that tremors have on human-made structures.

Although an earthquake's magnitude and intensity measurements are not precisely comparable, they can, in general, be correlated when intensity measurements nearest the epicenter are used in the comparison (fig. 2; Steeples and Brosius, 1996). Seismologists categorize earthquakes by their magnitude, not by their perceived intensity.

Earthquakes and the Potential for Induced Seismicity in Kansas

The majority of seismic events are microearthquakes, too small to be felt or to cause damage. The largest documented earthquake in Kansas, centered near Wamego east of Manhattan in 1867, rocked buildings, cracked walls, stopped clocks, broke windows, and reportedly caused ground to sink and endanger the bank of a canal near Carthage, Ohio (Parker, 1868). That earthquake was likely associated with the Nemaha Ridge, a 300-million-year-old buried mountain range extending roughly from Omaha to Oklahoma City. The Humboldt fault zone on the eastern boundary of the Nemaha Ridge is still slightly active (Steeples and Brosius, 1996). Based on damage and reports, the Wamego earthquake was estimated to have a magnitude of 5.2 (Niemi et al., 2004). Smaller faults and fault systems also have been identified in the state, mainly during oil and gas exploration, but none have been connected with large earthquakes.

At least 25 earthquakes in Kansas were documented in newspaper accounts and other sources between 1867 and 1976. A few of the later ones were recorded with seismic equipment. Between 1977 and 1989, the Kansas Geological Survey recorded more than 200 small earthquakes with a temporary seismic network as part of a study to identify seismic risk in the state (fig. 3). The monitoring equipment was sensitive enough to detect artillery fire at Fort Riley from 30 miles (50 km) away and large earthquakes as far away as Japan (Steeples and Brosius, 1996). Today, two seismic monitoring stations, operated by the U.S. Geological Survey, are located in Kansas. One is at Cedar Bluff Reservoir in western Kansas and the other is at the Konza Prairie Biological Station south of Manhattan in northeastern Kansas. The Oklahoma Geological Survey monitors earthquakes in Oklahoma at about a

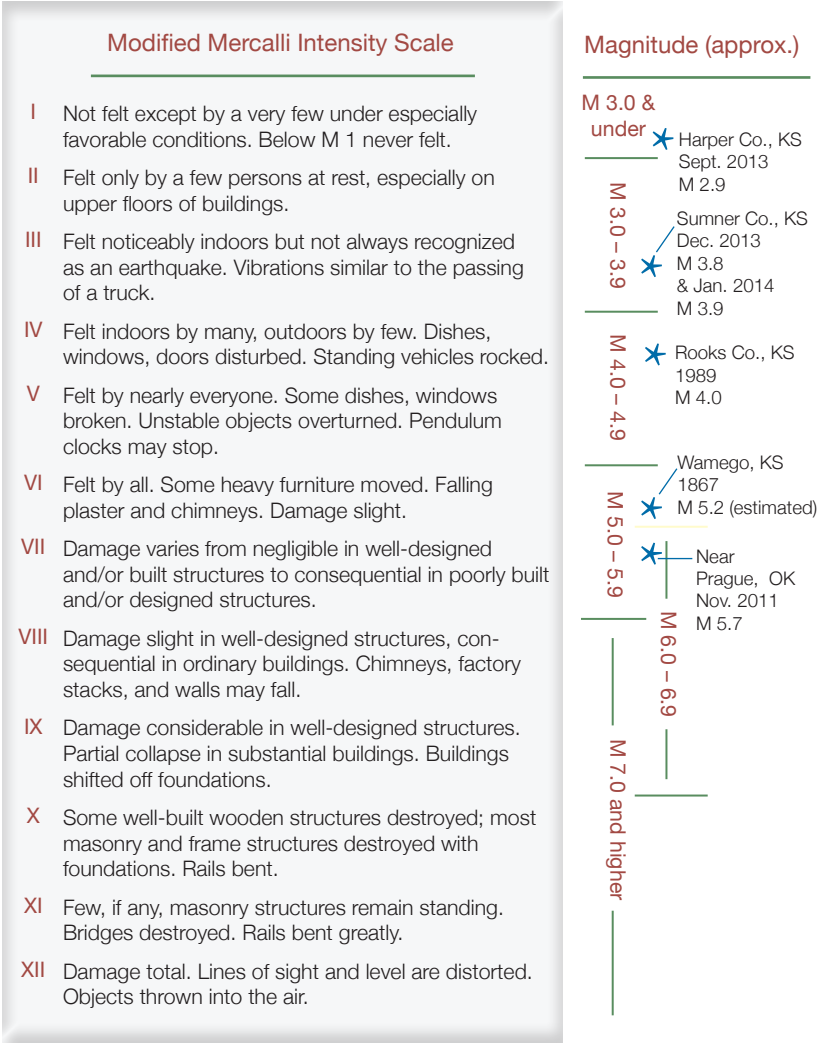

Figure 2—The magnitude (M), or size, of an earthquake does not correlate directly with intensity or damage, but an approximate comparison can be made between the magnitude and the felt intensity and damages—enumerated on the Modified Mercalli Intensity scale—near the epicenter (USGS, 2014).

dozen seismic stations, which also pick up some seismic events in Kansas.

Although oil and gas drilling and production, and corresponding wastewater injection, increased in south-central and western Kansas as interest in the Mississippian limestone play grew, the state has not experienced the same rise in seismic activity as neighboring Oklahoma. That may be due to the lower level of drilling and production activity in Kansas, differences in geology between the two states, or both. Oklahoma has historically had more natural earthquakes than Kansas. Also, the Oklahoma Geological Survey, which has been monitoring seismic activity for more than three decades, increased the size of its monitoring network in 2009 (Oklahoma Geological Survey, 2014). That led to the detection of a greater number of low-level earthquakes. Similar-sized events go unrecorded in Kansas.

In Oklahoma, a number of seismic episodes are suspected of being associated with induced seismicity. The largest, a M 5.7 earthquake, was recorded near Prague in 2011 (Keranen et al., 2013). Researchers are investigating whether injected fluid precipitated a M 5.0 foreshock that then triggered the M 5.7 mainshock and thousands of aftershocks along the Wilzetta fault system in central Oklahoma. The locations of the foreshock, mainshock, and a M 5.0 aftershock suggest that three separate portions of the complex fault system were activated (Sumy et al., 2014). A definitive connection between wastewater disposal and seismicity near Prague and several other Oklahoma locations with previous natural earthquake activity, however, has not been confirmed (Oklahoma Geological Survey, 2014).

Before 2013, the only documented instance of possible induced seismicity in Kansas occurred in 1989 when small earthquakes were recorded near Palco in Rooks County, about 30 miles northeast of Hays. The largest, a M 4.0, caused minor damage (Steeples and Brosius, 1996). Several injection wells used for the disposal of wastewater—extracted during conventional vertical oil well operations—were located in the area, and one well in particular may have been close to a deeply buried fault zone. Based on that well's injection history, local geology, and low level of prior earthquake activity in the area, scientists speculated that the seismicity could have been induced (Armbruster et al., 1989).

In 2013 and early 2014, several earthquakes were recorded in south-central Kansas in the vicinity of wastewater injection wells. In Harper County, a M 2.9 earthquake was recorded in September 2013, and in Sumner County earthquakes measuring M 3.8 and M 3.9 were recorded in December 2013 and February 2014, respectively (USGS, 2014). Whether oil activities played a role has not been determined. Naturally occurring earthquakes have been recorded in the region in the past, dating back to 1956. Further understanding of the complex subsurface geology in the region is needed to estimate what impact wastewater disposal might have had.

Geology, Faults, and Induced Seismicity

The Earth's crust is full of fractures and faults. Under natural conditions, widespread faults deep in the crust are able to sustain high stresses without slipping. In rare instances, pressure from wastewater injected into deep wells can counteract the frictional forces on faults and cause earthquakes (Hayes, 2012). In other words, fluid injected near a fault can, in effect, change pore pressure—the amount of pressure that fluid in a rock's pores exerts on the rock—allowing a fault to move.

For that to happen, a combination of human activities, natural conditions, and

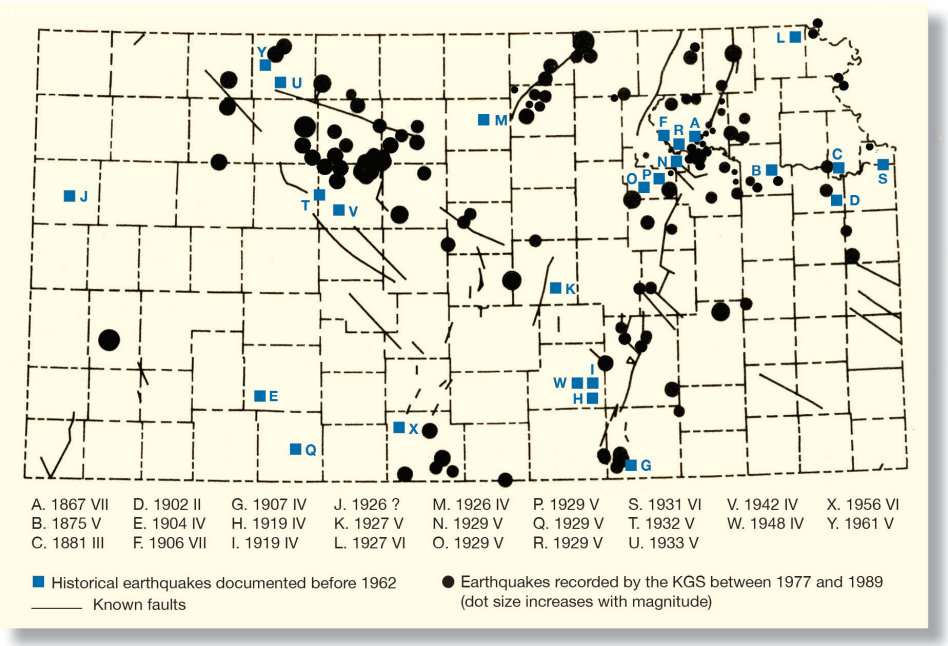

Figure 3—Historical earthquakes in Kansas before 1962 and seismic events recorded by the Kansas Geological Survey between 1977 and 1989 (modified from Steeples and Brosius, 1996).

geologic events must occur at the same time. To begin, the Earth's crust at the injection well site must be near a critical state of stress and an existing fault has to be nearby—within about 10 km (6 mi). Most faults are small and only generate small earthquakes. For a fault to slip and release energy, the location and orientation of the fault is critical. No matter how close a fault is to an injection well, its orientation within the ambient stress field and the properties of the surrounding subsurface rocks determine whether it has the potential to fail (National Research Council, 2012). If a fault does fail, the depth at which it ruptures influences its effect.

Even when all the natural conditions are favorable for induced seismicity near a disposal well, an earthquake is not a certainty. Under most circumstances, a significant amount of water must be injected over a prolonged period to activate a fault. As fluid is injected into the porous subsurface rock, the pore pressure would then have to increase to the point that it caused the volume of the rock to expand and destabilize a fault. Likewise, a decrease in pore pressure when fluid is extracted from rock can affect fault stabilization (National Research Council, 2012).

Many of the Earth's faults are in the Precambrian-age basement rock, which in Kansas lies beneath the deep and confined porous formations used for wastewater storage. Formed 500 million or more years ago, the basement rock is overlain by thousands of feet of **sedimentary rock**. Injected wastewater does not reach the basement rock, but if pressure created by the injection of fluid is transmitted into the basement through surrounding rocks, the potential for induced seismicity increases (Ellsworth, 2013).

Because of their depth, faults within the basement rock are hard to locate. Oil and gas exploration companies, which provide much of the data about the state's subsurface geology, rarely drill that deep. Seismic-reflection techniques used to identify subsurface rocks and faults are expensive and difficult to employ at that depth. Until more is known about the geology of Precambrian rocks, scientists will not be able to determine with certainty what effect wastewater disposal and other oil and gas field activities have on seismicity. A close spatial relationship between a wastewater disposal site and increased seismic activity, although it raises legitimate questions, does not prove cause and effect.

Hydraulic Fracturing, Wastewater Disposal, and Induced Seismicity

Hydraulic fracturing is at the center of the debate over induced seismicity in the United States. Microseisms, usually less than a magnitude of zero (M 0), do occur during hydraulic fracturing. In fact, geologists often record them to help identify the location of the newly made fractures and to measure stress. However, felt earthquakes have rarely been linked to hydraulic fracturing, and the ones that have been are relatively small (National Research Council, 2012). Two confirmed cases of felt seismic activity caused by hydraulic fracturing have been documented—a series of seismic events measuring up to M 2.3 in England in 2011 and a series of events ranging from M 2.2 to M 3.8 in a remote area of the Horn River Basin in British Columbia, Canada, between 2009 and 2011 (Holland, 2013; BC Oil and Gas Commission, 2012). Hydraulic fracturing also has been suspected of causing a M 2.9 earthquake in south-central Oklahoma in 2011, but that has not been confirmed (Holland, 2013).

Hydraulic fracturing is unlikely to cause felt seismicity because pressurization that occurs during the process usually lasts only a few hours and affects only rocks in the area immediately surrounding the well bore (Zoback, 2012). Wastewater disposal, in which fluids are injected over a longer period, is more often associated with induced seismicity. It has long been recognized that fluid injection can trigger earthquakes. Seismic activity following wastewater disposal at the **Rocky Mountain Arsenal** near Denver in the early 1960s and by water injection at the **Rangely oil field** in western Colorado in the late 1960s and early 1970s has been well studied (Zoback, 2012). However, although a large quantity of fluids is injected into hundreds of thousands of wells every year, only a small number of those wells have been associated with induced seismicity.

Wastewater Injection and Class II Disposal Wells

There are approximately 172,000 fluid-injection wells in the United States used to dispose of wastewater or to extract additional oil out of fields nearly depleted by traditional production methods. Of those wells, designated Underground Injection Control (UIC) Class II wells by the U.S. Environmental Protection Agency (EPA), about 20% are used for the disposal of saltwater that is produced along with oil and natural

gas. In the disposal process, saltwater is injected into a deep formation selected for wastewater disposal and not into the formation from which it was originally produced. Non-potable water and chemicals used in the hydraulic fracturing process, which must be disposed of under State of Kansas requirements, are also injected into these wells.

Most of the rest of the Class II wells are used during **secondary** and **enhanced oil recovery** operations to squeeze additional oil out of underground rocks (EPA, 2012). For these operations, saltwater is commonly injected back into the formation from which it was produced. The injected water, ideally, moves toward the production well, transporting additional oil to the well.

The EPA regulates the licensing and operation of Class II disposal wells under the Safe Drinking Water Act or delegates authority to state agencies. The act is primarily designed to protect aquifers and other drinking water sources from contamination by injected fluids. Class II well operators submit a form annually indicating total monthly injected volumes and the maximum monthly recorded surface injection pressure.

The Kansas Corporation Commission (KCC) regulates the approximately 16,800 Class II wells in Kansas. About 5,000 of those wells are for wastewater disposal and 11,800 for secondary and enhanced oil recovery (KCC, 2014). Class II wells are used only for the injection of fluids associated with oil and gas production. Hazardous and non-hazardous industrial waste, regulated by the Kansas Department of Health and Environment (KDHE), is disposed of in UIC Class I wells. There are 47 Class I wells in Kansas (KDHE, 2012).

In general, waste fluids from oil and gas production in Kansas are injected back into deep subsurface formations "under gravity." That is, because the formations can accept substantial amounts of fluid, fluids are not injected under additional pressure but are simply allowed to flow into these rock formations under the force of gravity. Gravity injection limits the possibility of pressure build-up in the disposal formation and reduces the potential for fault slippage. Often, any pressure increases that do occur from gravity injection are limited to the vicinity of the well, although the effects of gravity injection may extend farther out than anticipated. Force from fluid weight, independent of injection pressure, also can have an impact.

When fluids are pumped into a rock formation under pressure, rather than being allowed to flow more slowly under the force of gravity, the added pressure may lower the frictional resistance between rocks along an existing fault system. That allows the rocks to slide. In the Rocky Mountain Arsenal case, where chemical fluid waste was injected under pressure numerous times, seismic activity continued for several years after injection was discontinued (National Research Council, 2012).

Preventive and Remedial Measures

The authors of a National Research Council (NRC) report and others have suggested steps that could be taken to alleviate induced seismicity associated with Class II wastewater disposal wells. The recommendations are based on a protocol advanced by the U.S. Department of Energy to address induced seismicity associated with enhanced geothermal systems. To establish a protocol in a specific location, an evaluation would first have to be made to determine whether following suggested recommendations would be feasible in that location. Enactment would require coordination between industry, government agencies, and the research community; monitoring seismicity and collecting data; assessing hazards and risks; and developing mitigation plans (National Research Council, 2012).

The protocols are often referred to as "traffic light" systems. Under the systems, operators would continue injection as long as earthquakes did not occur (green light), would slow injection rates and take other precautions if seismicity occurred (yellow light), and would abandon wells if seismicity associated with injection did not slow significantly or stop after precautions were taken (red light). In instances of suspected induced seismicity in Arkansas and Texas, injection was terminated and seismicity subsided (Zoback, 2012).

An essential element of the traffic light system is the capacity to monitor seismicity and collect data. The current monitoring network in the United States, with its widely spaced stations in Kansas and many other states, can detect moderate to large earthquakes. However, it is less effective at pinpointing the epicenters of, or even recording, smaller events far from monitoring stations. Determining whether a connection exists between recent earthquakes and fluid injection wells in Kansas and elsewhere will require increased and more densely spaced monitoring stations closer to injection sites. Increased access to data pertaining to the injection process, especially the volume of fluid injected over a specified period and the amount of pressure used to inject it, is also vital.

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Glossary

Enhanced oil recovery—Production of trapped oil left in the ground following primary and secondary recovery operations. Gases, steam, or chemicals are injected through a Class II fluid-injection well into a producing formation to lower the viscosity of the remaining oil and allow it to flow to the producing wells.

Horizontal drilling—Drilling that starts out vertical then gradually turns in a horizontal direction to extend a greater distance into a known oil-producing zone.

Hydraulic fracturing—Injection of fluids and sand into a well to fracture oil-bearing rock layers. Colloquially called "fracking," especially when used in conjunction with horizontal drilling, hydraulic fracturing increases permeability in rocks to free trapped oil.

Mississippian limestone play—A complex group of oil and gas reservoirs within a shared geologic and geographic setting that extends from north-central Oklahoma into south-central and western Kansas.

Rangely oil field—An oil field in northwestern Colorado where the U.S. Geological Survey experimented with adjusting fluid pressure in injection wells between 1969 and 1973 to determine how changing injection rates could control seismicity.

Rocky Mountain Arsenal—Established in WWII, the RMA north of Denver was used by the U.S. Army to develop chemical weapons and was later used to produce agricultural chemicals. A deep injection well drilled there in 1961 for the disposal of hazardous chemicals was abandoned in 1966 after 13 earthquakes of M 4 or larger occurred. Earthquake activity declined but continued for two decades (Ellsworth, 2013).

Sedimentary rocks—Rocks formed from sediment, broken rocks, or organic matter, often deposited by wind or water and then compacted into layers after being buried under other sediment.

Secondary oil recovery—Production of residual oil and gas from fields whose reservoir pressures have dropped after initial, or primary, recovery using natural underground pressure and pumping. Water or gas is injected into a Class II fluid-injection well to increase pressure and force oil and gas to the surface through production wells.

Seismometer—Instrument used to measure ground motion and seismic waves generated by earthquakes and other seismic sources.

Tectonic plates—Massive, rigid plates in the lithosphere—Earth's outer shell—that are propelled from below by molten rock and that interact with one another along their boundaries, which can cause seismic activity.

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The mission of the Kansas Geological Survey, operated by the University of Kansas in connection with its research and service program, is to conduct geological studies and research and to collect, correlate, preserve, and disseminate information leading to a better understanding of the geology of Kansas, with special emphasis on natural resources of economic value, water quality and quantity, and geologic hazards.

The Geology Extension program furthers the mission of the KGS by developing materials, projects, and services that communicate information about the geology of Kansas, the state's earth resources, and the products of the Kansas Geological Survey.

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