GSA Critical Issue: Induced Seismicity

INTRODUCTION

The increase in oil and gas production from unconventional reservoirs has led to a concomitant increase in the need for wastewater disposal. Scientific evidence currently suggests that high-volume fluid injection in disposal wells in areas with hydraulic connection to sensitive geologic faults may induce seismicity. These faults may be unmapped or previously unknown.

This *Critical Issues* paper will cover the current state of science related to the cause, occurrence, and potential impacts of induced seismicity (earthquakes likely triggered by human activities) so that policy makers, journalists, and the public can more accurately understand the issue for better decision making related to safety, protection of property, and for developing energy and related regulatory policy.

Society has depended on hydrocarbons for energy and chemical feedstock for over 100 years. The extraction of hydrocarbons, as well as their refining and processing into thousands of chemicals, creates large volumes of liquid waste that require disposal. In addition, conventional reservoir oil and gas production, supplemented by a large increase in unconventional reservoir development, has led to an increased volume of formation brines (i.e., production water) and waste water from hydraulic fracturing (i.e., flowback water) being produced with the oil and gas, thereby necessitating disposal. With advances in drilling technology and engineering, these wastes have been successfully injected into deep rock formations capable of accepting the wastes for permanent storage. However, there have been occasions when unforeseen conditions encountered in the target rock formations have resulted in earthquakes that, in some areas, are correlated spatially and temporally to the waste injection process.

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In the past decade, North America has experienced a boom in oil and gas production[1] from unconventional reservoir rocks. The term “unconventional” relates to low permeability reservoir rocks (such as shale) that may contain significant oil and gas but do not readily yield hydrocarbons. However, advancements in drilling technology allow companies to drill vertically, then turn and drill laterally for thousands of feet, and then hydraulically fracture (frack) the rock to release the oil and gas. These lateral, near-horizontal well bores are targeted to align with the attitude and structure of a geologic formation that holds tremendous amounts of trapped oil or natural gas.

Horizontal drilling coupled with hydraulic fracturing uses water to transfer the hydraulic pressure needed to fracture the target rock. This water typically contains minor amounts of chemical additives and treatments (normally less than 5%) to transfer hydraulic forces more effectively (e.g., surfactants), as well as to enhance productivity (e.g., acids, biocides) in the target formation. Modern hydraulically fractured wells may require over 3 million gallons[2] of water for treatment. A by-product of both conventional and unconventional oil and gas production is formation water that is brought to the earth’s surface along with hydrocarbons—much of it in the form of brackish or concentrated brines. This saltwater waste, plus the flowback water from the hydraulic fracturing process, is either treated and recycled for further hydraulic fracturing, or handled as waste water needing disposal.

For decades, oil and gas producers have looked for economic ways to recycle, treat, reuse, or dispose of the wastewater. One common way is to recycle and reuse the wastewater for additional hydraulic fracturing. Sometimes water is re-injected into conventional oil fields to create a “water flood” where water, being a more dense liquid than crude oil, will force any remaining oil toward designated extraction wells. This water-flooding process is referred to as secondary recovery. If reinjecting water is ineffective in forcing additional hydrocarbons out of the reservoir, tertiary treatments, such as injecting carbon dioxide, may be used to further stimulate production. In other situations, the wastewater has no further use and is injected for permanent disposal into acceptable rock formations either deeper or shallower than the producing zone. The disposal of high volumes of fluids, over long periods of time, can alter the pressure conditions in the subsurface, potentially causing existing faults to slip, leading to seismic events (earthquakes). These earthquakes can be detected by instruments, or in some cases felt on the land surface in the vicinity of earthquake’s location. In rare cases, motion may be felt up to hundreds of miles away from the disposal wells[19]. To date, felt earthquakes related to disposal wells are not the norm and appear restricted to vulnerable regions. In Texas, there are approximately 7,500 active disposal wells and only a small number of reported cases of induced seismicity. However, some larger seismic events have been sufficiently powerful to cause moderate damage to buildings and structures on the land's surface near the injection sites[4].

The *Dictionary of Geological Terms*[3] defines seismic as "pertaining to an earthquake, or earth vibration, including those that are artificially induced." In nature, sections of the earth's crust can be under tremendous stress. When the stress exceeds the breaking point of the rocks, a failure or fracture usually results. If movement has occurred along the fracture, it is termed a geologic fault. Faults consist of complex surfaces of breakage, often approximately planar, and an earthquake occurs when rock on one side of the fault rapidly moves relative to the other. The release of the stress at the point of failure or along the fault results in an earthquake. Movement along the fault, which can be rapid or violent, and varying in the amount of displacement, dictates the size of an earthquake. In many cases, preexisting dormant faults and fractures in the crust will reactivate in response to stress at levels that are much lower in magnitude than would be required to fracture intact rock. Active geologic faults can be the origin of multiple earthquakes, while some faults become dormant over geologic time. Dormant faults can be reactivated at later times if a sufficient stress field, either natural or manmade, builds in the faulted rocks and exceeds the stresses holding the adjacent sides of the fault in place.

The earthquake movement releases energy that is transmitted through the earth's crust in a series of waves that cause the crust, and all things upon it (e.g., buildings) to move or oscillate in several directions depending on the size, orientation, and direction of the fault's movement, and how much displacement, or movement, occurs along the fault. The magnitude of an earthquake is an estimate of the amount of energy released by the fault motion. That energy is released at the hypocenter, which is the point (usually beneath the surface) of origin of the earthquake. The point on the surface directly above the hypocenter is called the epicenter. The severity of shaking caused by the earthquake at any one place, called the intensity, is related to the magnitude of the earthquake, but also the distance to the hypocenter, the types of rock and soil between the hypocenter and the point in question, and the depth of the earthquake. Other factors that affect the intensity of an earthquake, and how the earthquake is felt at the surface, are the types of rocks in which the waves are propagating and the time since the event occurred. All energy resulting from the quake will eventually be absorbed by the rock media and decay to the point at which it can no longer be felt or measured, which is termed attenuation.

Earthquakes are usually measured and reported in scales of magnitudes. Earthquake reporting can be confusing because different scales are often used (e.g., Ms, Mb, Ml, and Mw). These various magnitudes are related to the types of waves that are moving through the earth. For example, magnitudes related to surface waves (denoted with an "s") move in the earth's crust near the surface, versus body waves (b) that pass through the interior of the earth. Some of these scales are only appropriate for small or specific motion related to a specific earthquake. The moment magnitude (denoted by Mw or M) is valid for any size earthquake, so earthquakes magnitudes in this paper will most often be presented in terms of Mw. The Richter magnitude is often reported by the press, but for induced seismicity, the attenuation will often differ, so the shaking felt by residents may be greater for the same Richter magnitude than for other areas of natural seismicity. This difference is highlighted in seismic intensity maps where the response at the surface is mapped instead of at the origin of the earthquake.

INJECTION AND INDUCED SEISMICITY

Changes in the stress field occur when fluids have been withdrawn or injected into the subsurface. However, the details of exactly how the pressure change can cause slip, or movement on faults, are complex. For example, withdrawal of fluids can result in the lowering of subsurface pressures and thus cause earthquakes. On the other hand, the injection of fluids can substantially raise pressures, which can also induce earthquakes. Earthquakes tied to the withdrawal of oil during production were identified in the 1950s in California[4,5]. A current example associated with natural gas withdrawal is the active seismicity from gas fields in onshore areas of the Netherlands, where reactivation of existing faults is the hypothesized mechanism[6].

One of the earliest and most documented accounts of induced seismicity related to subsurface injection of fluids occurred at the Rocky Mountain Arsenal (Colorado), which is a federal reservation where chemical armaments were manufactured. Years of activities at the site resulted in large quantities of liquid wastes, which required disposal. A deep well (12,045 ft.) was drilled into the site, where it was determined that the rocks encountered at depth were capable of accepting fluids injected under pressure. Approximately 165 million gallons of liquid wastes were injected during the period from 1962 through 1966[4]. During this time, the injected fluids increased the pore pressure, reducing the stabilizing (normal) stress across the fault, resulting in earthquakes that occurred at rates that could be correlated with the volume and timing of fluid injections. The fluid injection was halted, and the felt seismicity ceased over several months. The location of the earthquakes also migrated westward, which demonstrated that the “pressure front” created by the fluid injection could migrate over time.

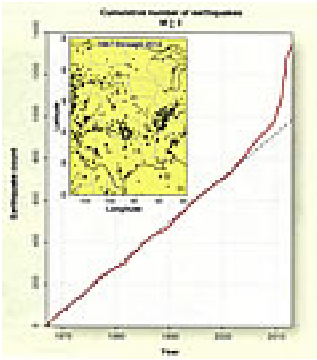

Figure 1:
Cumulative count of earthquakes with M >3 in the central and eastern United States, 1967–2012 (modified from Ellsworth, 2013).

Recently, areas of the United States that have had little or no seismic activity in the recent past have suddenly become seismically active[7,8,9]. For example, in the mid-continent of the United States, there has been an increase in earthquakes greater than Magnitude 3 (Figure 1). An average of 21 earthquakes per year greater than M3+ occurred in this region from the late 1973 to about 2008, but between 2009 to 2013, the average number of earthquakes greater than M3 increased dramatically to 99[10], correlating reasonably well with the increase in fluid injection that has taken place over the last decade. In several cases, the increased seismic activity has been linked to the injection of increasing volumes of waste fluids derived from increased oil and gas production. Arkansas, Ohio, New Mexico, Colorado, Texas, and Oklahoma have each experienced an increase in the number of measureable earthquakes, as well as an increasing frequency of earthquakes with Mw > 4. Moreover, the location of the quakes appears to be closely correlated with the location of deep injection wells, as well as to increased volumes of waste injected[9]. Earthquakes of M > 4 or even slightly less can result in some damage to buildings and structures. While these increases in the number and magnitude of earthquakes near injection sites are compelling, not all scientists agree that all of these events are related to underground injection[9] because some of the sites have been seismically active in the past. Current knowledge, technology, and historic data of questionable quality make establishing a direct link between correlation and causation difficult to confidently ascertain. Additionally, since many of the earthquakes occur at depths below the injection zones and migrate away from the wells over time, the patterns generated for evaluation are generally complex.

One of the major challenges for geoscientists trying to determine if seismic events are natural or human-induced is the lack of publically available examples of where integrated subsurface characterizations have been developed in areas suspected of having induced seismicity. A proper subsurface characterization should include an understanding of pore fluid pressure, both regionally and locally, and how it has changed as a function of operations; reservoir architecture, especially faults; reservoir flow data; and constraints on geomechanical properties and conditions. Clearly, reflection seismic, well and core, and reservoir engineering data are critical to constructing a proper subsurface characterization. Other important data include subsurface geology, fluid disposal characteristics (volume, pressure, etc.), and the pressures in the subsurface away from injection wells at a high temporal resolution.

The availability of quality seismometer data is also vital, but it has not been collected uniformly in all regions of the U.S. For example, much of the seismic monitoring in the U.S. has focused on regions of the country (e.g., California, upper Mississippi Valley) prone to natural seismicity related to the movement of earth’s tectonic plates. The central and mid-western regions of the country, which have traditionally been more stable, have had less robust seismic networks, or have seismic stations separated by large distances. Small earthquakes (M <2.0), which are the magnitudes of the vast majority of earthquake clusters typically observed around injection wells, are thus incompletely detected or located. In addition, injection wells are often drilled thousands of feet deep—some exceeding 10,000 feet—into zones where the geology and the three-dimensional nature and orientation of fracture systems and faults are unknown, except for the rock immediately adjacent to the well bore. Preliminary observations suggest that disposal of waste fluid into strata that overlie, and are hydraulically connected to underlying crystalline ”basement” rocks (which may have potentially active faults), could trigger earthquakes[11,12].

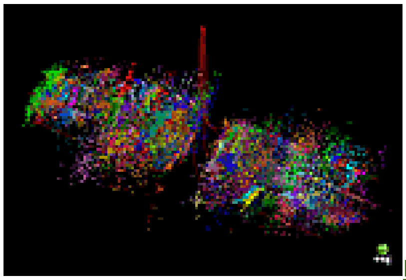

Figure 2:

Shell Oil Company well. Microseismic clusters along fracked lateral wells. The different colored dots represent microseisms recorded in controlled, individual zones fracked sequentially along a lateral well. Each microseism is <0.8 magnitude, which is approximately 2,000 times less energy than a magnitude 3.0 (typically felt) earthquake (https://www.esgsolutions.com/oil-and-gas).[22]

Does the hydraulic fracturing process in production wells cause induced “felt” earthquakes? Hydraulic fracturing has been used successfully for decades, and many scientific studies report no direct correlation of significant earthquakes with active hydraulic fracturing stimulation operations[8]. The hydraulic fracturing process, however, is designed to create small-scale fractures or faults in a localized area around the well bore, which is where the name of the process is derived. Figure 2 shows the zone of rock subject to small magnitude earthquakes along lateral wells that have been hydraulically fractured. When successful, the localized fracturing creates “mini” earthquakes, or microseisms (Mw <1). These can be measured and located accurately by highly sensitive seismic equipment used to monitor and direct the process while it is occurring, but the microseisms are rarely large enough to be felt at the surface, because the rock thickness between the zone being hydraulically fractured and the ground surface can be significant (>5,000 feet), thus attenuating these small earthquakes. However, recent reports suggest that under specific geologic conditions, hydraulic fracturing can be correlated to slightly larger earthquakes (Mw= 1 to 3). Such events were reported in Ohio (M = 3)[13], Oklahoma (M_w = 2.9)[14], the United Kingdom (M_w = 2.3)[15], and British Columbia (M_w = 3.8)[15]. Several studies suggest that the total volume of fluid injected to induce fracturing was a more important factor than the pressure level with regard to inducing seismicity.[13, 14, 15, 16]

OTHER SOURCES OF INDUCED SEISMICITY

Any process that involves either withdrawing earthen materials (e.g., coal) or fluids (e.g., hydrocarbons), or injecting large volumes of fluid (e.g., chemical wastes) is capable of significantly altering the in-situ subsurface stress field and can induce seismicity. Injection of wastes from hydrocarbon production has been highlighted in this paper as a major contributor, but other industrial, construction, and mining processes can induce seismicity. Examples include the extraction of brines for solution mining (e.g., salt) or for mineral production (e.g., lithium-rich brines) and deep coal mining[16].

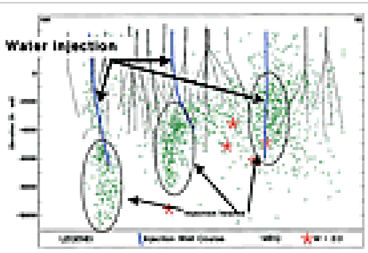

Figure 3:

Induced seismicity associated with injection at The Geysers geothermal field, California. Microearthquakes with M <2 are shown as green dots. Those with M >2 are shown as red stars. [ref]

Geothermal projects generally are located in tectonically active areas where naturally occurring geothermal fluids circulate in fractured rock or sediments. Wells are drilled into a geothermal reservoir to bring these high-temperature fluids to the surface, where they are used for direct heat (direct use) or to generate electricity (thermoelectric). The cooled fluids are then injected back into the hot rock reservoir to pick up heat and circulate it back to the surface[18]. At some locations, such as the Geysers geothermal field in California, injecting this cold water back into the hot reservoir causes thermal effects that result in seismicity. Figure 3 shows the relationship between water injection and seismicity at the Geysers geothermal field.

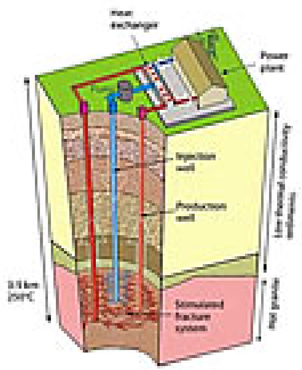

Figure 4:
Schematic of an enhanced geothermal system (EGS) power plant with injection and extraction wells and a stimulated fracture system (source: DOE).

In some areas of the world, high temperature rocks are close to the surface. Termed Hot Dry Rock (HDR), these reservoirs don't have sufficient natural fractures or permeability to allow natural geothermal fluid circulation to pick up and transfer the heat. Several projects in Europe now use stimulation with cold water injection at moderate pressures to create an artificial or enhanced geothermal system (EGS) to enhance natural fractures and allow injected fluids to pick up heat (Figure 4). Experimental designs have been considered to hydraulically fracture a HDR reservoir—that is, to artificially create permeable rock to allow efficient circulation and to capture the heated groundwater and exploit the geothermal energy. Once such an engineered or EGS is operational, the introduction of fluids will alter the pore pressure, which can potentially result in induced seismicity. In addition, the recirculation of relatively cold water will cool the hot rock, potentially inducing thermal contraction, which will reduce the rock volume and pressure, and can also result in seismicity[18]. EGS systems have been developed in Austria, Germany, France, Japan, Sweden, Switzerland, and the United States. In each case, some small-magnitude induced seismicity was observed[11]. In one case near Basel, Switzerland, an induced seismic event tied to an EGS project resulted in minor damage in the vicinity of the test site. More importantly, the induced seismic event took place near a relatively populated area with historic buildings, so the Swiss Government terminated the project.

Another cause of induced seismicity is the loading of the earth's crust with a large mass, such as a reservoir of water behind a large dam. In this case, not only is the mass of water altering the stress field, but water under high hydrostatic pressure created by the overlying impounded water body can drive water into the rock mass beneath the dam, increasing the pore pressure that can result in seismicity. It has been postulated that several earthquakes around the globe, including large events in India and China, were the result of reservoir loading[10]. This is not generally an issue for smaller dams because the amount of water in storage in not sufficient to induce seismicity.

REGULATION FOR UNDERGROUND INJECTION

Table 1. The six categories or "classes" of injection wells, along with their estimated national inventory for each class*

Classes	Use	Inventory
Class I	Inject hazardous wastes, industrial non-hazardous liquids, or municipal wastewater beneath the lowermost USDW.**	680 wells
Class II	Inject brines and other fluids associated with oil and gas production and hydrocarbons for storage.	172,068 wells
Class III	Inject fluids associated with solution mining of minerals beneath the lowermost USDW.	22,131 wells
Class IV	Inject hazardous or radioactive wastes into or above USDWs. These wells are banned unless authorized under a federal or state groundwater remediation project.	33 sites
Class V	All injection wells not included in Classes I–IV. In general, Class V wells inject non-hazardous fluids into or above USDWs and are typically shallow, on-site disposal systems. However, there are some deep Class V wells that inject below USDWs.	400,000 to 650,000 wells[#]
Class VI	Inject carbon dioxide (CO_2) for long-term storage, also know and geologic sequestration of CO_2.	6–10 commercial wells expected to come online by 2016.[##]

*Source: Water.epa.gov.
**USDW—underground source of drinking water.
[#]An inventory range is presented because a complete inventory is not available.
[##]Source: Interagency Task Force on Carbon Capture and Storage.

The U.S. EPA regulates the underground injection of fluids (water, waste, CO_2) under the Safe Drinking Water Act. In some cases, individual states have been granted primacy for regulating injection wells under the guidance of EPA. Underground injection regulations were designed to protect fresh groundwater and aquifers through a permitting or licensing process. Typically the permitting process requires the evaluation of fundamental scientific information regarding the geology of a proposed injection site, as well as technical specifications pertaining to well integrity, injection pressures, and the location of injection zones deep below the zone of fresh water. Currently EPA lists six categories of injection wells (Table 1). The injection of oil and gas waste fluids is handled by Class II injection wells. The injection of geothermal fluids is handled as Class V wells. According to EPA estimates, there are currently more than 172,000 Class II wells permitted in the U.S. As induced seismicity becomes a potential issue in a new area, these regulations need to be evaluated to determine if the wells are engineered to prevent seismicity as well as protect freshwater resources.

MITIGATION EFFORTS

Society's needs depend on natural resources for consumer products, building materials, and energy, and indirectly, the extractive industries that produce them. As presented in this Critical Issue Paper, extractive activities can disturb the earth's crust—be that near the surface (large reservoirs, open-pit mining) or deep underground (waste water injection, coal mining). One potential outcome of these activities is induced seismicity—in some cases resulting in "felt" earthquakes of sufficient size to damage property. The number and magnitude of induced earthquakes has increased in the past decade, which has created challenges for industry (particularly the oil and gas sector) and the regulatory agencies that oversee them. Increased seismicity has also elevated the level of concern from elected officials and the general public in areas afflicted by these events. However, as we broaden our scientific knowledge regarding the variables that control induced earthquakes, understanding them also offers a window into mitigation strategies that can help manage the associated risks to where they can be balanced with the value and need to extract resources or manage wastes, and these greatly benefit society.

State agencies regulate oil and gas production within their jurisdictions, and those states granted primacy for underground injection control (UIC) also regulate produced waste water in Class II injection wells (see Table 1). In states without UIC primacy, UIC programs are implemented by the U.S. EPA. Waste-water injection has been identified as the activity most responsible for the rise in induced seismicity in the U.S. in recent times. The success of hydrocarbon exploration and production, as well as efficacy of waste injection, is dictated by the local geologic framework, along with other factors. Typically, the most comprehensive publically available geoscience data and information is held by state geological surveys, local universities, and state regulatory agencies. However, the origin, source, organization, and accessibility of this data and information vary from state to state, to some degree. Data that already exist from these sources have not yet been fully synthesized. Augmenting these data with subsurface and operational data from the oil and gas industry, which collects important information, would contribute to a better understanding of induced seismicity.

Partnerships between state and federal agencies and academic researchers are important and can include data sharing of reservoir attributes and geologic data necessary to develop ground-motion models, reservoir frameworks, and engineering properties that are critical to developing methods and tools to minimize induced seismicity. These partnering efforts can lead to safer, long-term fluid injection practices that minimize seismic hazards and risks. Several state agencies, as well as research groups, have begun compiling factors that should be considered when developing risk management protocols and tools to assist with mitigating potential seismicity. For example, Walters[18] and others have compiled a list of factors that can be considered for conducting risk assessments for population centers and infrastructure in the proximity of well injection sites. Consistent with these recommendations, Oklahoma is requiring more comprehensive monitoring of seismic activity and injection volumes, and is developing injection schedules and cycles to manage injection and reservoir pressures to reduce the likelihood of induced seismicity. Guidance for preparing mitigation strategies, and science-based risk strategies, are presented by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission[20].

In Europe, the International Energy Agency has developed a protocol for induced seismicity associated with enhanced geothermal systems (EGS), which is being applied in the EU for all EGS projects[21]. In the U.S., the Department of Energy has developed an induced seismicity mitigation protocol that all EGS projects that comply with NEPA must follow[22]. The steps for the U.S. DOE protocol are shown below:

- Step 1: Perform a preliminary screening evaluation.
- Step 2: Implement an outreach and communication program.
- Step 3: Review and select criteria for ground vibration and noise.
- Step 4: Establish seismic monitoring.
- Step 5: Quantify the hazard from natural and induced seismic events.
- Step 6: Characterize the risk of induced seismic events.
- Step 7: Develop risk-based mitigation plan.

SUMMARY

This Critical Issues Document is intended to furnish policy makers, regulators with oversight for developing natural resources, members of the Geological Society of America, and the interested public with a concise, clear, and non-technical discussion of the causes of induced seismicity, as well as to serve as a reference for non-geologists.

Society needs natural resources that are extracted from the earth. Any process that involves either removing (e.g., hydrocarbons, ores) or injecting (e.g., chemical wastes) large volumes of fluids is capable of altering the fluid pressures and in-situ stress field in the earth’s crust, which can induce seismic activity. Geoscientists play a critical role in all parts of the induced seismicity phenomenon—not only from our role in discovering and developing energy and mineral resources, but also characterizing the subsurface geology to better identify the stress fields, previously unknown faults, fracture systems, subsurface reservoir storage potential, and other variables that allow society to make better decisions regarding extraction of subsurface fluids and the disposal and management of wastes. Geoscientists are always looking for improved and efficient ways to generate or capture existing data regarding rock-mechanical characteristics, which can aid our ability to develop better predictive models for reservoir behavior.

Seismologists are working to deploy high-resolution seismic monitoring networks that can enhance subsurface characterizations and improve numerical models to better predict thresholds that precede seismic events. Even with cogent conservation efforts, the world will demand more energy and resources in the future, and it is imperative that geoscientists be involved in the discussions and decision-making related to energy policy, resource development, and waste management.

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GLOSSARY

Aquifer: A body of permeable rock or sediment that is saturated with water and yields useful amounts of water.
Biocide: A chemical substance capable of destroying some life forms. In hydraulic fracturing, biocides are used to inhibit growth of bacteria and mold.
Chemical feedstock: The raw material used in the manufacture of chemicals. For example, natural gas methane is a chemical feedstock for ammonia and formaldehyde.
Conventional reservoir: Oil and gas have migrated, often long distances, from its source into permeable layers before being trapped by geologic structures and stratigraphy; these can often can be extracted without stimulated production.
Fault: A fracture or fracture zone along which rock layers have moved.
Flowback water: The fracturing fluid that returns to the surface through a wellbore during and after a hydraulic treatment.
Formation: A basic unit of rock layers distinctive enough in appearance, composition, and age to be defined in geologic maps and classifications; the identifying characteristics are laterally extensive, perhaps for up to hundreds of miles.
Fracture: A crack or break in the rock.
Hazard: Any sort of potential damage, harm, or adverse impact on something or someone.

Hydraulic fracturing: A process to propagate fractures in a subsurface rock layer with the injection of pressurized fluid through a wellbore, especially to extract oil or gas.
Hydrocarbon: An organic compound made of carbon and hydrogen, found in coal, crude oil, natural gas, and plant life.
Mercalli intensity scale (MI): Used by scientists to measure the size of an earthquake in terms of effects at the earth's surface (e.g., levels of damage to buildings and their contents).
Moment magnitude scale (Mw or M): Used by scientists to measure the size of earthquakes in terms of the energy released. The scale was developed in the 1970s to improve upon the Richter magnitude scale, particularly to describe large (M >7) earthquakes and those with an epicenter is over 370 miles away.
Microseismic: A faint earth tremor Mw <1; typically less than Richter Magnitude zero, which was the detection limit in 1935.
Permeability: The capacity of a rock for transmitting a fluid. Permeability depends on the size and shape of pores in the rock, along with the size, shape, and extent of the connections between pore spaces.
Pressure front: The leading edge of a zone of high pressure that is moving through a body of rock in the direction of lower pressure.
Produced water: The naturally occurring fluid in a formation that flows to the surface through the wellbore, throughout the entire lifespan of an oil or gas well. It typically has high levels of total dissolved solids with leached out minerals from the rock.
Reservoir rock: The oil or gas bearing rock, typically a fractured or porous and permeable rock formation.
Richter magnitude scale: A numerical scale previously used by scientists to measure the size of an earthquake, ranging from <0 to >9.
Risk: The chance or probability that a person or property will be harmed if exposed to a hazard.
Seismic event: An earth vibration, such as an earthquake or tremor.
Shale: A fine-grained sedimentary rock that formed from the compaction of finely layered silt and clay-sized minerals ("mud"). It typically has low permeability, which makes it difficult to obtain oil or gas using conventional production methods.
Unconventional reservoir: Tight deposits such as shale and other rocks with low porosity and permeability. The gas or oil remains in the layer in which it was created or migrates short distances and requires stimulated production to extract.
Well bore: A hole that is drilled to explore and recover natural resources, such as oil, gas or water.