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Making the Earth Shake: Understanding Induced Seismicity

A discussion of the possibility of induced seismicity resulting from natural gas drilling in the Marcellus Shale.

Introduction

Pennsylvania, West Virginia, and New York State are areas of interest for the commercial extraction of natural gas from a layer of sedimentary rock called the Marcellus Shale. Companies are leasing land and drilling both test and commercial wells throughout the region. There have been concerns that the techniques used to extract the gas from this shale could cause earthquakes or "seismicity" in the region.

The Marcellus Shale is made of clay particles, mud, and organic material that were deposited at the bottom of a shallow sea around 390 million years ago. Since then, the deposited material has been compressed into rock and some of the organic matter has turned into natural gas. Unlike in typical gas reservoirs, the Marcellus Shale traps the gas in tiny isolated pore spaces, keeping it from migrating and pooling into large reservoirs that can be tapped by conventional drilling techniques. Hydraulic fracturing, a process used in Marcellus Shale natural gas extraction, uses water and chemicals under high pressure to break the rock and create pathways that connect the pores, which allows the gas to flow into wells for extraction.

DID YOU KNOW?

- A group of earthquakes without a clear main shock is called a swarm.
- The largest recorded earthquake in New York was a magnitude 5.8 that occurred near Massena on September 5th, 1944.
- It is estimated that, globally, over 500,000 earthquakes occur each year, with only around 100 large enough to cause damage.

How Earthquakes Are Generated

An earthquake is usually generated by a sudden movement in the Earth's brittle outer layer or crust, releasing built up stress. This movement most often occurs along pre-existing faults, which are fractures in the Earth's crust. This, in turn, generates violent shaking and releases energy that is transmitted by vibrations, known as seismic waves. These seismic waves radiate through and along the surface of the earth.

The San Andreas Fault System in California is a well-known example of a group of faults along which movement often occurs, triggering earthquakes. Like the San Andreas, most active fault systems are located along the plate boundaries that make up the Earth's

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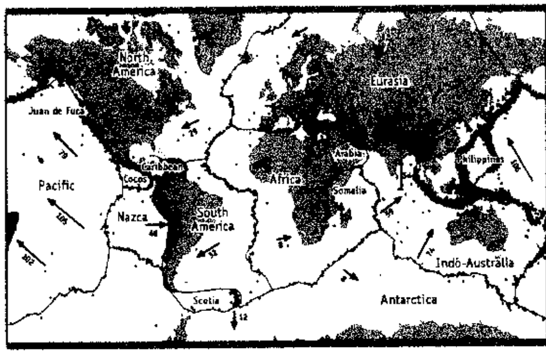


Fig. 1. Map of current plate boundaries throughout the world. Arrows indicate the speed and direction of plate movement, represented in millimeters per year. Dots indicate the presence of earthquakes, which are concentrated along plate boundaries. Notice how the dots concentrate when two plates are moving toward each other, and are less common where plates are moving away from each other. This image is courtesy of Incorporated Research Institutions for Seismology (IRIS), and is part of their educational series of pamphlets about earthquakes that can be accessed online at http://www.iris.edu/hq/publications/brochures_and_onepagers/edu.

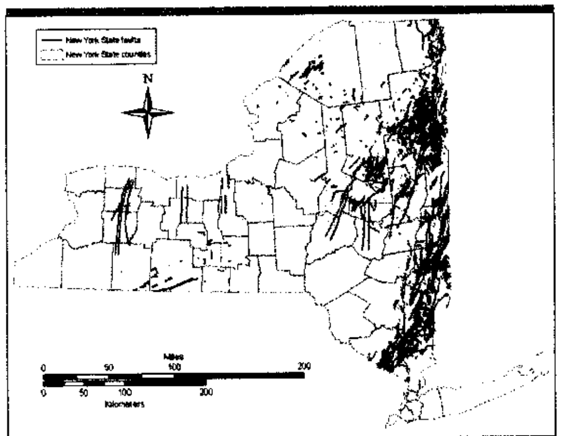
crust and upper mantle. New York is far from the current boundaries of the North American plate, as can be seen in Figure 1, but has been near plate boundaries repeatedly during the geological past. As a result, it has a series of fault systems of different ages. Some of these fault systems, like the one underlying the Appalachian mountains, can be traced across the continent. Individual faults in the system can extend across one, or even several county lines and are mostly concentrated in the eastern portion of the state. Relatively inactive today, many of these faults originated during the continental plate collisions that formed the supercontinent Pangea around 300 million years ago.

The strength of an earthquake is determined by the amount of energy released by the earth movement. Large earthquakes result in ground shaking and movement that can be felt for hundreds of miles from the epicenter, the point on the Earth's surface directly above where the earthquake originated. Small earthquakes are significantly more common, but are almost never felt, even by the residents living close to epicenters of the earthquakes. These can only be detected by sensitive equipment like seismometers.

The relative size of an earthquake has been historically measured by the Richter scale, which has now been replaced with the similar, but more precise moment magnitude scale (MMS). Using this scale, scientists rate the magnitude of an earthquake by measuring the size of the recorded seismic waves. MMS is represented on a logarithmic scale, where a 1-unit increase in magnitude on the scale corresponds to a 10-fold increase in the size of the recorded wave. It also roughly corresponds to a 30-fold increase in the amount of energy released. Thus, the amount of energy released during a magnitude 3.0 earthquake is approximately one thousand times more than the amount of energy released during a magnitude 1.0 earthquake.

The Modified Mercalli intensity scale is used to describe the level of ground shaking at a given location around the earthquake source, and approximates the likely resulting damage. Earthquake damage depends, in part, on the amount of energy released during the earthquake, but also on the distance from the earthquake source, the type of rock, and other geological factors. Usually, in New York and adjacent states, an earthquake with magnitude less than a 1.5 is almost imperceptible. It might only be felt by a few people near the epicenter, and would not cause damage. A magnitude 7.0 or greater earthquake

Fig. 2. Map depicting the location of both active and inactive faults within New York State.[1] *Lines denote the location of faults, usually found beneath the surface. Note the high concentration of faults near the eastern state boundary. Image courtesy of M. Weltman-Fahs.*



Relating Earthquake Magnitude and Intensity

Modified Mercalli Intensity (near source)	Description	Effects	Maximum Moment Magnitude
I	Instrumental	Not felt except by a very few under especially favorable conditions.	0 to 2.0
II	Feeble	Felt only by a few persons at rest, especially on upper floors of buildings.	
III	Slight	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.	1.5 to 3.0
IV	Moderate	Felt indoors by many, outdoors by a few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.	2.0 to 4.0
V	Rather Strong	Felt by nearly everyone: many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.	4.0 to 5.0
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.	5.0 to 5.9
VII	Very Strong	Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary structures, considerable damage in poorly built or badly designed structures, some chimneys broken.	
VIII	Destructive	Damage slight in specially designed structures: considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.	6.0 to 6.9
IX	Ruinous	Damage considerable in specially designed structures: well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.	
X	Disastrous	Some well-built wooden structures destroyed: most masonry and frame structures destroyed with foundations. Rails bent.	
XI	Very Disastrous	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.	7.0 and higher
XII	Catastrophic	Damage total. Lines of sight and level are distorted. Objects thrown into the air.	

Modified from USGS Earthquake Hazard Program: *http://earthquake.usgs.gov/learn/topics/mag vs int.php*

Table 1. Comparison of the moment magnitude scale and the Mercalli scale. The moment magnitude scale is based on the amount of energy released in an earthquake while an earthquake on the Mercalli scale is rated based on observations of the effect of an earthquake on the Earth's surface.

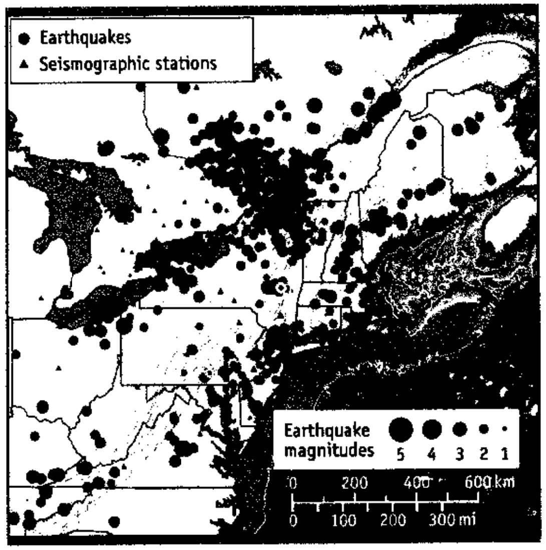


Fig. 3. Earthquakes in the Northeast U.S. and Canada from 1990-2010. Image courtesy of Won-Young Kim, Lamont-Doherty Earth Observatory of Columbia University.

would likely cause considerable building damage and destruction of an area. Table 1 compares the magnitude of an earthquake to the maximum intensity, or extent of damage that would likely result close to the earthquake, based on the Modified Mercalli Intensity scale.

Understanding Induced Seismicity

Induced seismicity is earthquake activity that is the direct result of human activity. Humans can significantly alter the state of stress in the shallow portions of the Earth's crust in many ways that can trigger, or "induce", earthquakes. Examples of natural stress in the Earth's crust are the weight of the overlying rock or the collision of plates. Induced earthquakes are triggered when the natural stress is already close to failure, the point at which a fault becomes active and causes an earthquake. Surprisingly, the stress in rocks is normally close to failure, even in geologically stable areas like New York.

Several recent earthquakes in New York and surrounding states have been shown to be human-induced. More may have been induced, but proving an earthquake has been triggered by human activity is difficult. It requires showing that the stress change caused by humans is sufficiently large, in the right direction, and at the right time to have caused the earthquake. This proof, therefore, requires detailed information about both the earthquake and the human activity that could have triggered it.

Furthermore, fluid in the rock ("pore fluid") plays a key role in the state of stress and in the rock failure leading to earthquakes, because rising pressure in this fluid weakens the rock. This pressure can take some time to change because fluid migrates slowly through the rock, so that an induced earthquake can occur years after the human activity that induced it has stopped. Thus, a swarm of earthquakes can be related to human activity even if the earthquake occurs later, making identifying induced seismicity difficult.

Sometimes seismic waves are intentionally generated, like in geophysical surveys. Geophysical surveys map the layers and structures underneath the Earth's surface by controlled explosions or pounding the ground with weights. The energy used in such exploration surveys is much too small to induce a natural event of any measurable size. On a larger scale, nuclear explosions have been known to trigger "natural" earthquakes.

New York State Earthquake Activity

Understanding the potential for induced seismicity as a result of natural gas drilling in the Marcellus Shale in New York requires knowing the background levels of seismic activity in the region. This is normal seismicity that occurs on a regular basis due to natural events, like rock failure, and regular human activities such as automobile traffic. Between December, 1970 and July, 2009, over 800 seismic events were reported throughout New York. Of these, 180 were located in areas underlain by potentially commercial gas shales, the Marcellus and Utica Shales. Only 9 of these events were greater than a magnitude 3 and 'felt' outside the immediate vicinity of the earthquake epicenter.[2]

Generally, earthquakes below a Magnitude 2 go almost unnoticed by people and magnitude 3, if felt, are not often recognized as earthquakes.

Earthquake activity is monitored in New York by the United States Geological Survey (USGS) and the Lamont-Doherty Cooperative Seismographic Network (LCSN). LCSN has 40 seismic recording stations located throughout the northeastern U.S., one of which is hosted by the Paleontological Research Institution. Each station contains a ground motion sensor called a seismometer.

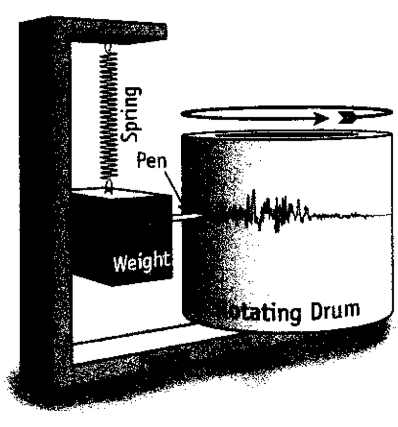
In principle, seismometers have a frame placed in a vault at the Earth's surface that suspends a weight from a spring. As the Earth moves during a seismic event, the relative motion between the weight and the frame provides a recorded measure of the vertical ground motion. This information allows scientists to measure the size of the earthquake, and, with data from several other stations, to locate the origin of the earthquake.

The Role of Water in Induced Seismicity

Hydraulic fracturing requires injecting large quantities of water into rock under very high pressure in order to crack the rock. When any fluid is injected into a rock unit, there is a possibility that it can migrate to an existing fault or fault system, raising the fluid pressure at the fault. The resistance to slippage along a fault depends on the fluid pressure: the higher the pressure, the more likely the fault will slip, resulting in an earthquake. Thus, an increase in fluid pressure can provide enough additional stress on the fault to re-activate it, triggering an earthquake. This is why there is concern that hydraulic fracturing could induce earthquakes in New York.

Some of the fluid used in hydraulic fracturing is returned to the surface and must be disposed of. One disposal method uses deep injection wells to pump the waste water into deep rock formations for permanent storage. These wells reach down deep into the bedrock where most natural earthquakes are known to occur. Some of these wells in Ohio, and even in New York, have been shown or are suspected to have triggered induced earthquakes.

Fig. 4. Basic diagram of a seismometer. Image courtesy of IRIS, accessed online at http://www.iris.edu/hq/publications/brochures_and_onepagers/edu.



Cases of Induced Seismicity in NY State

In the last four decades, there have been three recorded seismic swarm events in New York that have been correlated with human activity and classified as induced seismicity. They were located in Cuylerville, Avoca, and Dale, NY. These towns are situated just west of the Finger Lakes in central New York and fall within a 60 mile radius of each other.

Case No. 1: Cuylerville, NY

On March 12, 1994, a small portion of the 6,000 acre Retsof Salt Mine collapsed as a result of the failure of several salt pillars holding up the overlying rock. The collapse resulted in a sudden release of energy and was recorded as a magnitude 3.6 earthquake by a handful of seismic stations up to about 300 miles away. The initial collapse allowed groundwater to enter the mine from above at a rate of 5,000 gallons per minute, which dissolved additional salt pillars and lead to the eventual collapse and flooding of the entire salt mine.[3] Ultimately, mining led to the de-stabilization of the overlying rock units and collapse of the mine, making the magnitude 3.6 earthquake and accompanying seismic activity "induced" by human activity.

Case No. 2: Avoca, NY

On February 3, 2001, a magnitude 3.2 earthquake was recorded near Avoca, NY. The area had been undergoing testing for a natural gas underground storage facility. A vertical well was hydraulically fractured, then was repeatedly injected with recycled fracturing fluids to dissolve a salt layer in the rock, making room for the New Avoca Natural Gas Storage facility (NANGS). Investigations revealed that local residents noticed increased seismicity at the same time fluid injection began, and that seismicity stopped shortly after injection was stopped. Once test injection activity ceased in the area, no additional seismic activity was recorded or felt by residents, according to LCSN.[4]

Case No. 3: Dale, NY

In 1970, background seismicity levels near Dale had averaged less than 1 event per month. However, in 1971, a drastic increase in seismic events, up to 80 per day, was recorded. While frequent, the earthquakes were never greater than magnitude 0.8. During 1971, the Texas Brine Corporation, a salt mining company, converted a salt mine in Dale into a deep fluid injection storage facility. Several times when fluid was being injected, seismic events were recorded. Less than 48 hours after fluid injection ceased, seismic events were no longer recorded.[5]

Investigation showed that prolonged fluid injection allowed the fluid to migrate to a nearby fault zone, which resulted in the dramatically increased seismic activity near Dale. Because the quantity of seismic events was dramatically greater than background seismicity, and this increase in seismicity was correlated in time with fluid injection, this swarm of events was determined to have been a case of induced seismicity.

Deep Fluid Injection and Hydraulic Fracturing

Hydraulic fracturing has been commercially used by the oil and gas industry to fracture rock units since 1949. Originally, hydraulic fracturing used much smaller quantities of water at lower pressures than it does today in horizontal wells in the Marcellus. Presently, there are no known or inferred cases of induced seismicity in New York resulting from the process of hydraulic fracturing. Induced seismic events in New York remain the result of deep fluid injection and mining. Because the Avoca and Dale case studies are linked to fluid injection, it is important to consider whether hydraulic fracturing could cause a similar effect.

Presently, there are no known or inferred cases of induced seismicity in New York resulting from the process of hydraulic fracturing.

Deep fluid injection is a method of permanently storing waste fluid in a deep rock unit, usually at least several thousand feet below the surface. Hydraulic fracturing in the Marcellus is a method that uses fluid to create numerous small fractures into a rock unit in order to extract another fluid, like natural gas or water. While both activities push fluid into a rock unit under high pressure, there are substantial differences in the processes.

Deep fluid injection constantly pumps fluid into the storage well at a moderate rate – roughly averaging around 300 gallons per minute – over the course of weeks or months, until the injection well can hold no additional waste, eventually containing millions to billions of gallons of waste fluid.

In shale gas extraction, like that used in the Marcellus, hydraulic fracturing injects around 3-5 million gallons of fluid into a well under extremely high pressures and at average rates of 3,000 gallons per minute. When this pressure exceeds the strength of the rock, fractures are formed and/or enlarged. This process is a discrete event that occurs over the course of hours to days, with a portion of the fluid returned to the surface.

Deep fluid injection is more likely than hydraulic fracturing to induce fluid migration over large distances and to trigger earthquakes for several reasons. In deep fluid injection, waste fluid is often injected at greater depths where substantial earthquakes are most likely to occur, and with a steady flow under constant pressure, ultimately permanently storing up to billions of gallons of fluid in a rock unit. In contrast, hydraulic fracturing forces a much smaller amount of water into a rock unit over a much shorter time frame, with a portion of that water returning to the surface.

It is not impossible for the type of hydraulic fracturing associated with Marcellus Shale gas drilling to induce seismicity. However, because it occurs on a much shorter time interval and at relatively shallow depth, there is less time for fluid to migrate to an existing fault system and cause seismic activity. Fluid pressures are also tightly monitored in a hydraulic fracturing operation to avoid the fracture extending beyond the shale itself, otherwise gas is lost into the surrounding formation. As the shale itself is a very weak material, it is unlikely to have stored up enough stress that the additional stresses of hydraulic fracturing would result in a seismic event. Thus, the probability of hydraulic fracturing producing induced seismicity is far less than from deep well injection.

The probability of hydraulic fracturing producing induced seismicity is far less than from deep well injection.

Induced Seismicity in the Barnett Shale

The Barnett Shale in the Dallas/Fort Worth region, Texas, is an important analog for the potential of induced seismicity in the Marcellus Shale. Natural gas in the Barnett Shale has been extracted with hydraulic fracturing since the mid-1990's, which makes it a good place to examine the potential for induced seismicity from these techniques.

In the settlement history of the Dallas/Fort Worth region, there had been no seismic events 'felt' by people inhabiting the area until October 31, 2008, after which a swarm of seismic events with magnitudes up to 3.3 occurred through 2010. Investigation of the earthquake swarm determined that earthquakes were located within a mile from one another and, on average, less than 1/3 of a mile from a deep fluid injection well. This well had become active in September, 2008, only seven weeks before earthquake activity began. It was concluded by Cliff Frohlich and others at University of Texas-Austin and Southern Methodist University that the injection of waste waster into this disposal well, and not hydraulic fracturing, was the likely trigger of induced seismicity in the Barnett Shale region.

The Dallas/Forth Worth earthquakes of 2008-2009 appear to be a rare instance of induced seismicity. Over the last 15 years approximately 12,000 wells were drilled and hydraulically fractured, and about 200 deep fluid wells were created to dispose of the waste created by the process. In June 2009, approximately 50 miles southwest of Dallas in Cleburne, TX another series of seismic events began, but so far they have not been studied in enough detail to ascertain if they were induced.[6]

Other Potential Sources of Induced Seismicity in NY

Natural gas drilling and wastewater disposal through deep fluid injection are not the only industries to use hydraulic fracturing and/or high volume fluid injection. In fact, any industrial activity that forces fluids into the Earth's crust can induce a seismic event. Both enhanced geothermal systems (EGS) and carbon capture and sequestration technology (CCS) use hydraulic fracturing and fluid injection processes that have the potential to induce seismicity.

Enhanced geothermal systems are designed to extract energy in the form of heat stored beneath the Earth's surface using water as a medium to transport heat from inside the Earth to the surface. A geothermal system that is enhanced has been hydraulically fractured to increase the permeability of the heated source rock. Then water is pumped through the rock, and heat from the rock is transferred to the water, which is carried to the surface and its heat converted to electricity.[7] The hydraulic fracturing process is also somewhat different for EGS than it is in gas-shale extraction. For EGS, the process is largely involved in reopening old sealed joints, rather than creating new fractures.

Recently, the most newsworthy cases of induced seismicity have been associated with EGS. In 1982, the largest known earthquake event resulting from EGS (magnitude 4.6) occurred 60 miles north of San Francisco, CA. On August 15, 2009, a Magnitude 2.7 earthquake was recorded in Landau, Germany, originating 1500 feet from a local geothermal plant with EGS. Basel, Switzerland recorded a series of earthquakes, the strongest 28 ranging from magnitude 1.7 to 3.4 in December of 2006. The Cooper Basin in Australia and an area in Alsace, France recorded EGS-induced seismic events in 2003, with magnitudes 3.7 and 2.9, respectively.[8] It is important to note that all hydrothermal regions are naturally very seismically active, and thus have a much higher potential of seeing induced seismicity.

Carbon sequestration, which can also require hydraulic fracturing, also has the potential to induce seismicity. In carbon sequestration, large volumes of carbon dioxide (CO_2) are compressed and injected into a rock unit, and sometimes hydraulic fracturing is used to increase the permeability of the rock unit to allow greater CO_2 storage.

In order to maximize the volume of CO_2 that can be stored underground, it is injected at extreme pressures that change the normal behavior of the gas. As a super-pressurized liquid, CO_2 can change the characteristics of the rock into which it is deposited. It can cause the formation of new minerals in the rock pores and fractures, which can drastically lower the amount of space available in the rock for the CO_2; this in turn can increase pressure within the rock, and ultimately cause an earthquake. CO_2 can also dissolve minerals in the rock, re-activating local faults and causing earthquake activity.[9] However, since the goal of sequestration is to keep CO_2 in the rock, the intention is to keep the injection pressure below values that would fracture the rock or reactivate an existing fault. This technology, for the most part, is still in the testing phase of development.

Implications for Marcellus Drilling

Human activities involving changes in weight on the surface and/or changes in fluid pressure in rock have triggered earthquakes. Some of these earthquakes were large and damaging. Processes that involve prolonged periods of high pressure well injection at great depth are more likely to induce earthquakes than short-term well stimulation by hydraulic fracturing at the depths associated with the Marcellus Shale. Sometimes, both hydraulic fracturing and deep fluid injection are used together as parts of a larger process (e.g. the Avoca case study), which is why both have been implicated in induced seismicity. In Marcellus Shale natural gas drilling, deep fluid injection appears to be much more likely to cause induced seismicity than hydraulic fracturing.

According to Dr. Leonardo Seeber, a seismologist and senior researcher at Columbia University's Lamont-Doherty Earth Observatory, "the evidence so far suggests that triggered and natural seismicity in tectonically stable regions [such as New York State] cover the same magnitude range and that triggered seismicity adds significantly to the natural seismicity, proportionally increasing the hazard". This means that induced earthquakes are not likely to be larger or more hazardous than natural earthquakes in an area, although human activity can substantially increase the number of earthquakes a region experiences.

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