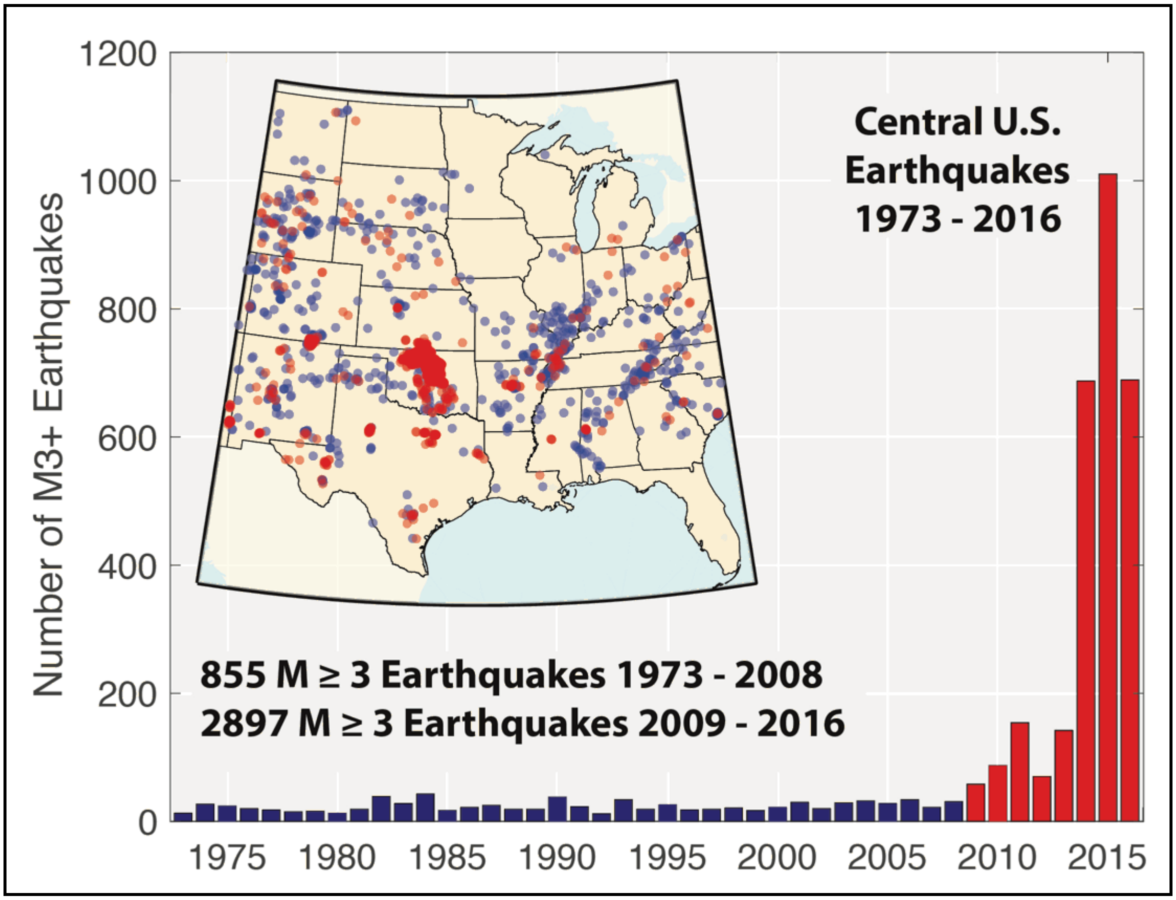
On March 16th Will Yeck presented "The Far-Reaching Effects of Wastewater Injection: Recent Studies of Anthropogenic Earthquakes" at the monthly meeting of the Colorado Scientific Society. Dr. Yeck works at the National Earthquake Information Center of the USGS in Golden, CO. The talk included different cases of induced seismicity, beginning with cases in Colorado, which have provided much instruction about what is understood about these earthquakes. Past studies can be compared and applied to recent cases of earthquakes that are related to fluid injection.

The Natural Earthquake information Center of the USGS in Golden is part of Geologic Hazard Science Center on the Colorado School of Mines campus where seismicity is characterized in real time. The mission of NEIC is to 1) determine as rapidly and as accurately as possible, the location and size of all significant earthquakes that occur worldwide. The NEIC disseminates this information immediately to concerned national and international agencies, scientists, critical facilities, and the general public; 2) collect and provide to scientists and to the public an extensive seismic database that serves as a foundation for scientific research, principally through the operation of modern digital national and global seismograph networks and through cooperative international agreements. The NEIC is the foremost national data center and archive for earthquake information; and 3) pursue an active research program to improve its ability to locate earthquakes and to understand the earthquake mechanism. These efforts are all aimed at mitigating the risks of earthquakes to the global population. NEIC monitors earthquakes worldwide, 24/7, with 17 analysts that work round the clock. Approximately 2500 seismic stations report to NEIC globally and earthquakes can be reported within 20 minutes of the occurrence. NEIC maintains an earthquake website where the public can report earthquakes and what was felt.

Any time stress is changed in the subsurface there is the potential to generate an earthquake. Historically these earthquakes have been associated with reservoir impoundment, where the weight of the water causes stress changes and changes in fluid pore pressure. Generally, these are the largest earthquakes that have been triggered by humans. The largest, a magnitude 6.3 in India, killed about 150 people.

Another activity that can trigger earthquakes is mining. These events are generally small, but a magnitude 5.4 earthquake has occurred. Geothermal production involves fluid injection and extraction and can induce seismicity. Most earthquakes from geothermal activities are small, although a large earthquake of magnitude 6.6 occurred in Baja Mexico. The largest earthquake that has been induced in the US by geothermal activity is magnitude 4.6, in California at The Geysers. The Geysers is the world's largest geothermal field and is a place where activity was expected to trigger earthquakes; therefore a system was established to allow people to make claims based on damages that occurred due to the operations.

Earthquakes induced from oil and gas extraction are generally small. Most news reports linking fracking to earthquakes are not valid. Fracking commonly causes small earthquakes that are not felt. Recently in Alberta Canada there have been many more earthquakes that have been tied to fracking directly, the largest of which is a magnitude 4.6, but generally fracking not a cause of induced seismicity.



From the USGS Website

Injection of wastewater, which is a by-product of oil and gas extraction, can cause earthquakes, the largest of which was a magnitude 5.8 that occurred in Pawnee, Oklahoma last year. Production can generate 10 bbl of wastewater / 1 bbl oil, and it is eliminated by injecting it into a zone that is under-pressured, the most economical solution. Injection does increase pore pressure, and if a fault is located nearby that is critically stressed, i.e. close to failure, an earthquake could be triggered. The rate of earthquakes, which was fairly constant from 1975-2009, has dramatically increased, causing news. The majority of induced earthquakes have been in north-central Oklahoma, the Raton Basin of Colorado, and also in the Dallas/Ft. Worth area--everywhere where wastewater is being extracted and injected. The question has been raised as to whether the up tick is due to additional seismic monitoring stations and the answer is no. Historically, all of the magnitude 3 earthquakes were large enough to be captured on previous stations. As the records are valid, it appears conditions have changed to produce the increased seismicity.

Colorado is the site of two classic studies that showed that earthquakes can be triggered. The Rocky Mountain Arsenal was the first instance where it was learned that injection can induce earthquakes. Prior to this Denver was largely aseismic. Injection started in 1962 with high volumes of fluid, and correlated with seismic activity. There were periods when the well was shut down, and seismic activity stopped. In 1966 the well was shut down but seismic activity actually continued for a long time. A magnitude 4.9 earthquake afterwards caused damage to an overpass. Because of this sequence it was learned that seismicity can continue even after injection stops, which was instructive for interpreting events in Oklahoma.

The activities at the Arsenal inspired the field test at Rangely, Colorado, where seismologists constructed an experiment to determine if earthquakes could be controlled. The working hypothesis was that fluid pressure changes could trigger earthquakes. The project was designed to inject at depth, monitor downhole pressure, and observe how the rate of seismicity changed. In the larger picture, scientists were interested in finding out whether earthquakes could be controlled, and if so, could strain on faults such as the San Andreas, be alleviated. Would injection slowly release the strain, creating smaller earthquakes that could prevent a larger earthquake? Even then this was not borne out at the Arsenal , where a very large earthquake occurred after injection had ceased. There is not good control on the size of the earthquakes that can be induced and exactly when they might occur. But the Rangely experiment did confirm that humans could cause earthquakes. A graph of results showed the correlation between injection and increase in fluid pore pressure. With an increase in pore pressure there was a concomitant increase in the principal stresses, effectively reducing the normal stress on a fault. An analogy would be to observe the forces on a block sitting on a slope, which tends to slide down but is held by gravity. If water is added, there is a decrease in this force that causes the block to slip. If a fault is critically stressed and the normal stress is decreased, there can be rupture.

The Paradox Valley is one of the best cases of induced seismicity in terms of the history and the data available. The project is a desalinization project for the Colorado River. Salty water is extracted from the Dolores River, which is a tributary of the Colorado, and moved to an injection well where it is injected underground, at 4-4.8 km. Engineers understood that there was the potential to induce earthquakes when conceiving the project, and therefore, monitoring stations were installed prior to start-up to obtain background readings of seismicity. The records provided a history of small earthquakes prior to injection. Data collection began in 1985 and injection tests started in 1991. Water was extracted near the surface, moved, and then injected into the Mississippian Leadville formation and also into the basement rocks, immediately producing seismicity. An injection hiatus ensued. In 1996 injection started full time, which triggered a magnitude 4 earthquake. Injection has continued more or less since then. There have been well shut-ins, periodically, to attempt to lower the downhole pressure, and an actual diffusion of earthquakes can be observed away from the well. At the inception of injection, earthquakes were concentrated close to the well, and over time moved farther and farther away. Now there are earthquakes about 20 km away from the well, a distance comparable to that from Lakewood to Evergreen, widespread effect.

The Paradox Valley earthquakes closely reflect the regional geology. Early in the project the earthquakes occurred close to the well before expanding out to the northwest. Eventually they began to wrap around the valley anticline, and recently seismicity has been experienced directly under the valley. It is important to understand that the earthquakes are occurring in patches and clusters, and are really an effect of where the critical stress faults are located (often unknown) and how the pore pressure is diffusing. The study also shows the effect with distance from the well: Close to the injection well, increased downhole pressure correlates well with seismicity; 5-10 km away, that relationship is not as clear.

Induced injection raises questions as to what could be the largest magnitude earthquake that can be induced at a given well and whether seismicity is scaled with injected volume. In the Paradox Valley a correlation has been observed between the magnitude of seismicity over time, the area affected, and the volume of injected fluid. The seismicity also provides information on the size of a fault in that area. In the Paradox Valley the size of the rupture area scales well with the magnitude earthquake. Also, an evaluation of the length of faults prior to their rupture, if possible, might provide an idea of how large an earthquake would occur. What has been learned from the Paradox Valley is that earthquakes can occur "large" distances from injection wells; downhole pressures can affect the rates of seismicity near the well but farther from the well that is not always the case; and the subsurface geology is critically important to where these earthquakes occur.

Greeley, Colorado experienced a magnitude 3.2 earthquake on June 1 2014 in a region that was considered to be aseismic previously. There was one well that was injecting at high rates located near this earthquake, high rates of injection considered to be in the range of 300,000 bbl /mo. This earthquake was thought to be induced, but the closest seismic station was about 100 km away and there was not a good history of the seismic sequence. But after a few events and aftershocks, it was possible to cross correlate to see how those sequences may have evolved in the past. About 54 earthquakes were detected using the distance stations 100 km away-- 31 of them were new events prior to the magnitude 3.2 earthquake that weren't reported or weren't felt.

There is a record of monthly injection rate at two wells associated with the earthquakes, a C4 well which was injecting at lower rates, and a C4A well that was co-located and injecting at higher rates closer to the basement. An earthquake was observed a couple of months after the C4 well began higher rates of injection. The mitigation involved plugging back to a different zone of injection, changing the schedule of injection to decrease the volume, and then slowly increasing injection again. Much less seismicity occurred after these efforts.

Regulators have established what is known as the "Traffic Light System" based on the magnitude earthquake that occurs near a well. For example, if a magnitude 4 earthquake occurs within 4 km, the operator can be given a red light to stop injecting. Other mitigations that have proven effective are to avoid connectivity to basement and avoid injecting near active faults. Most of the seismicity is occurring in the basement, below where injection is occurring.

The scenario in Oklahoma is more complex because there are thousands of injection wells throughout the state, rather than the more simple case of a single well inducing seismicity. Around 2009 and especially in 2013, the rate of earthquakes dramatically increased. Historically the rate had been one to three magnitude 3 earthquakes in the state. This changed to the point where there have been about 1000 earthquakes a year of that size, which is a dramatic shift. In 2011 there was a magnitude 5.7 earthquake. In 2016 there were three earthquakes of magnitude 5: the Fairview at 5.1, the Pawnee at magnitude 5.8, and the earthquake in Cushing. In the last 2 years, the rate of earthquakes has actually started to decline in Oklahoma.

The earliest record of an earthquake in Oklahoma was in 1882, with a magnitude 4.8-5.7, depending on the investigator. The location was poorly known as well, as some accounts place it in Texas. Oklahoma has seen not just increase in small earthquakes but an increase in larger earthquakes causing more damage. It has been fortunate that most of the large earthquakes recently have occurred away from population centers. The earthquake near Cushing caused the most damage—it was shallow and located closest to a city. Seismicity occurs in areas of higher fluid injection.

In some areas seismometers were placed after events to better pinpoint the location of aftershocks and back-calculate the location of the main event. This has helped the state build a good catalogue of earthquake location and size. Earthquakes are associated with strike slip earthquakes on or near vertical faults, and are most commonly in the basement. Injection is into the Arbuckle group, which overlies the Precambrian basement.

The Fairview earthquake was the largest to occur since the 2011 Prague earthquake. It is the second magnitude 5 earthquake that may have been induced in Oklahoma. Seismicity occurs on steeply dipping strike-slip faults deeper than many other earthquakes, at 6-10 km below MSL. Most events occur at the 4-6 km range. It is common that aftershocks will ring the area of maximum slip. It is notable that the Fairview earthquake shows broad- reaching effects of injection wells. Most of the wells are about 15 km northeast of the sequence and seismicity is fairly diffuse. There are only a few large earthquakes associated with injection in this area. It appears that as the pore pressure migrated it ultimately encountered a fairly large critically stressed fault that was large enough to host a fairly large earthquake, resulting in the Fairview sequence. This scenario emphasizes the importance of knowing the location of critically stressed faults to determine where earthquakes might occur. This is the unknown factor and runs contrary to the idea that seismicity is a function of the volume of injection.

A magnitude 5.8 earthquake in Oklahoma on September 3, 2016 occurred on an unmapped structure and was actually large enough to show displacement of the earth’s surface from satellite. The sequence has been quiet, with not many foreshocks or aftershocks with one magnitude 3.7. The earthquakes occur in the basement.

How effective are mitigation strategies for earthquakes? The Fairview sequence was very active. A month prior there was a day with three magnitude 4 earthquakes 4.4, 4.4, and 4.7 all within a 4-hr period, providing an idea that something was happening on this fault. This was followed by a month's quiescence before a magnitude 5.1 earthquake with a very vigorous aftershock sequence.   It might be concluded that there was some warning that the sequence was going to occur and that regulators could have employed the traffic light scenario to prevent that large earthquake. But lessons from the Paradox Valley have shown that the changes at the well don't instantaneously affect the far field.   It is unlikely that changes in response to the earthquakes (foreshocks) would have had an effect on triggering that main shock. More important, an examination of moderate induced earthquakes, Prague, Pawnee, and Cushing sequences, shows that most of them have very little foreshock activity. It would not have been possible to prevent these earthquakes with a traffic light system just because there was no forewarning that they were going to rupture. At Cushing the earthquake was near a very large oil reserve, a critical piece of infrastructure. There was a sequence of earthquakes in 2014 in response to which injection was shut down in the region. After a fairly long period of quiescence the magnitude 5 earthquake occurred. The conclusion that could be reached is that there is not great control over where earthquakes are going to occur based on changes in injection.

Could injection be avoided near critically stressed faults? These faults are not well mapped. Every one of the moderate earthquakes in Oklahoma has occurred on a previously unmapped structure. The Prague earthquake showed the extension of a fault that was mapped in the basement. Fairview was the same case. The Pawnee earthquake revealed a fault splay. The data is not always available, partly because not much effort has been expended into mapping faults in the Precambrian basement.

Oklahoma began wide-scale mitigation effort with a regional reduction of the volume of injection beginning in 2016. The goal was to reduce the injection volume by 40% of the 2014 value in a region of about 26,000 sq km. This is an ongoing experiment to determine whether earthquakes can be controlled. However, because of the low price of oil, it has been seen that the volume of fluid injection is actually less than what has been directed by OCC (based on information from OGS) . There are fewer earthquakes and consequently fewer larger earthquakes.   Some take home messages from studies on induced earthquakes are: large earthquakes can occur after injection stops; as pore pressure continues to diffuse it can encounter critically stressed faults that will trigger a large earthquake; earthquakes can occur 10s of km from the injection well; the locations of faults that might trigger an earthquake are often unknown. These factors may draw into question the mitigation methods that rely on constraining activity.

Comments based on audience questions.

There is no difference between natural earthquakes and induced earthquakes.
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Is there evidence that seismicity would relieve the stress over time and therefore seismicity? There is no evidence in Oklahoma, where there has been an increase in seismicity with an increase in injection and vice versa. Maybe in the Paradox Valley where there is an aseismic ring around the well. It may be that stress has been relieved on all of the critically stressed faults that have slipped. But pore pressure may increase to the point that it triggers a fault that was less optimally oriented to slip.

The Pawnee earthquake was felt all the way from San Antonio to Wisconsin. There is nothing that can be done once the earthquake ruptures. The wave decays with distance from the earthquake but the effect depends on the subsurface rocks.

Why are there slips 2-3 km below point of injection? How does water migrate down? It is not the water that is inducing these faults, but the pore pressure change. There are fractures in the Precambrian basement that transmit the pressure pulse.   This might be a question for a hydrogeologist.

Does the oil industry have an alternative method for disposing of the waste fluid? There is nothing cost effective. Desalinization is possible. The price of oil would need to skyrocket for this to be feasible. But, it is possible to try injecting into a different location.

What did Texas and Oklahoma do before when they were bigger oil producers? Was less water produced? Was it dumped in the river? Operators are working these plays that produce much more wastewater. There was wastewater injection going on in Oklahoma historically but it was at volume rates that were much lower. It is totally possible that injection can occur at a rate that does not induce earthquakes,. Greeley is a case in point. There was a well there that was receiving water for a long time, not near the basement, and didn't seem to be causing earthquakes. But when there is a high enough increase in the rate, and consequently, pore pressure, seismicity can be induced. That is really the basis of the mitigation effort, that there is some injection rate at which you will not trigger earthquakes.

Is there something specific to the crust in Oklahoma, that operators could inject anywhere and could cause earthquakes? There are regions where there are injections and no seismicity, where something is different. It may be the rates and volumes of injection. The crust is fairly fractured, and it is stressed everywhere. There are probably critically stressed faults everywhere and injection occurs at high enough pressure, an earthquake could probably be triggered.

When did the mitigation start, what were the main mitigations imposed as a result of the seismic activity?   In Oklahoma mitigation started in 2014 on a small scale and then ramped up.   It wasn't until last year that regional mitigation attempts began. The strategy was to stop injection within 3 km of a sequence, to reduce injection rates at 6 km.

How are regulators dealing with the idea of unknown faults being the cause of the problem? OCC is reviewing a very broad region, covering all of the seismicity that has been observed. The agency is agnostic about whether earthquakes are occurring on a preexisting structure or not. Going forward it is important to realize that locations of many faults are unknown.

Has this been affecting the permitting of injection wells now? I don't know if you can start a new well injecting into the Arbuckle. My sense is that it's very hard.

Is the strike-slip connection general or just in Oklahoma. Just in Oklahoma. In Kansas and Greeley, normal earthquakes are seen.

Is there any effort to map the stress distribution in the basement?   Much of what we know about the crust is due to earthquakes.

It wasn't too long ago that these were considered mysterious earthquakes, and there was denial from Oklahoma and the previous state geologist, about the injection connection. The studies are a testament to the people gathering data at USGS, an example of scientists working together to help people live better lives.