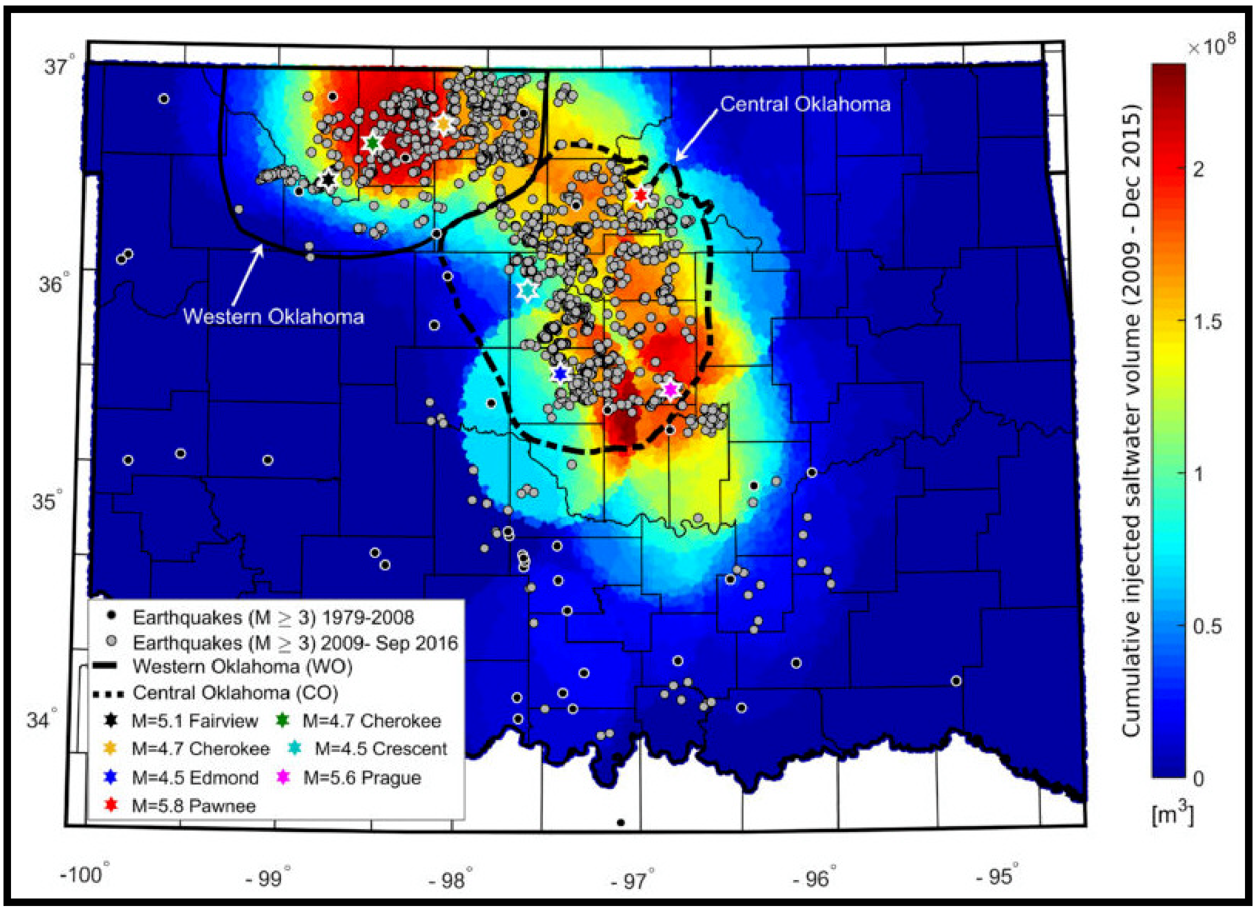
On March 2, Jeremy Boak of the Oklahoma Geological Survey (OGS) presented a talk on "Oklahoma Earthquakes and the Injection of Produced Water" at the Colorado School of Mines Van Tuyl lecture. The authorization of OGS is written into the state constitution, the only GS to be have this directive. They are mandated to operate with a state university and are located at Norman. OGS is charged with investigating the state's land, water, mineral and energy resources and disseminating the results of the studies to promote the prudent use of natural resources. OGS is not a regulatory agency, and once they took the position that the pulses of earthquake activity were related to waste water disposal by injection, the oversight shifted to the Oklahoma Corporation Commission, which regulates the oil and gas industry.

OGS and USGS monitor different earthquake stations within the state. The current earthquake study comprised data from 500 stations. Magnitude is a scale estimate of energy and different methodologies provide different answers. Magnitude is a scale estimate of energy released as seismic waves. It's proportional generally to the rupture area, or how much a fault has moved, and is measured multiple ways. The methods most commonly used are the focal magnitude, which is the classic Richter magnitude, largely from the first arrivals; and the moment magnitude. The larger earthquakes are generally measured by moment magnitude. The measurement scale is logarithmic: as the scale is increased by 1 in magnitude, the increase is 10x in the amount of shaking and 32x in the amount of energy released. The magnitude 7.1 earthquake in Alaska last year released more energy than all of the earthquakes in Oklahoma between 2009 and now. In the last 55 years there have been only five earthquakes of about magnitude 9, and these have released 15-20% of seismic energy in all geophysical recorded history: the 1960 Chilean earthquake, the 1965 Alaskan earthquake, the 2004 Sumatra earthquake, the 2011 earthquake in Japan, and another Chilean earthquake in 2015 that's been bumped up to 9. For comparison, an average tornado releases energy equivalent to a 4.8 magnitude earthquake and energy in a large lightning bolt is equivalent to 3.2 magnitude.

Earthquake intensity is measured on the modified Mercalli scale, which measures from 1, nobody notices, to 12, everything is flat. USGS has released a 2016 study on risk of a damaging earthquake, the occurrence of earthquakes that would cause actual damage to buildings. The highest probability is just over 10%, for any kind of damage at all. Home buildings in the state have not been constructed to the same kind of seismic code as California buildings. The modified Mercalli level 6 is the first level that shows damage to unreinforced structures,

Oklahoma previously had on average one to two earthquakes of magnitude 3 or greater per year. The observation area used to be so quiet that the original seismological observatory was chosen as to be one of the three threshold test ban treaty sites where Russians were allowed to come to the US and monitor the US nuclear testing program because there would be no interference from natural phenomena. In 2015 and most of 2016 there were three magnitude 5 earthquakes. The largest earthquake was magnitude 5.8, and a magnitude 5.0 occurred near Cushing, which is the site of the largest storage area of petroleum products in the nation.

Oklahoma may be the earthquake capital of the conterminous US, based on the number of earthquakes, but these are magnitude 3 earthquakes, peanuts compared to California earthquakes. If all Oklahoma earthquakes in 2009 were integrated regarding energy released and turned into a single earthquake, it would equate to a magnitude 6.1 earthquake. In 2014 California had a magnitude 6.1 and a 6.8 earthquake.



From Langenbruch and Zoback (Stanford 2016)

Earthquakes in Oklahoma occur in the northwest and central parts of the state. with the north-trending Nemaha and Rosetta faults marking the boundaries of the provinces. These larger faults are perpendicular to the closure stress, and large earthquakes are not found there. Many earthquake clusters align with faults trending NE-SW. They also occur in strike-slip faults aligned with an east-west stress field.   About half of earthquakes are occurring on faults that had never been seen before and seismic activity has allowed faults to be mapped or extended. Most of the faults haven't moved in the Paleozoic or Mesozoic and are identified as Pre-Cambrian faults that are being reactivated.

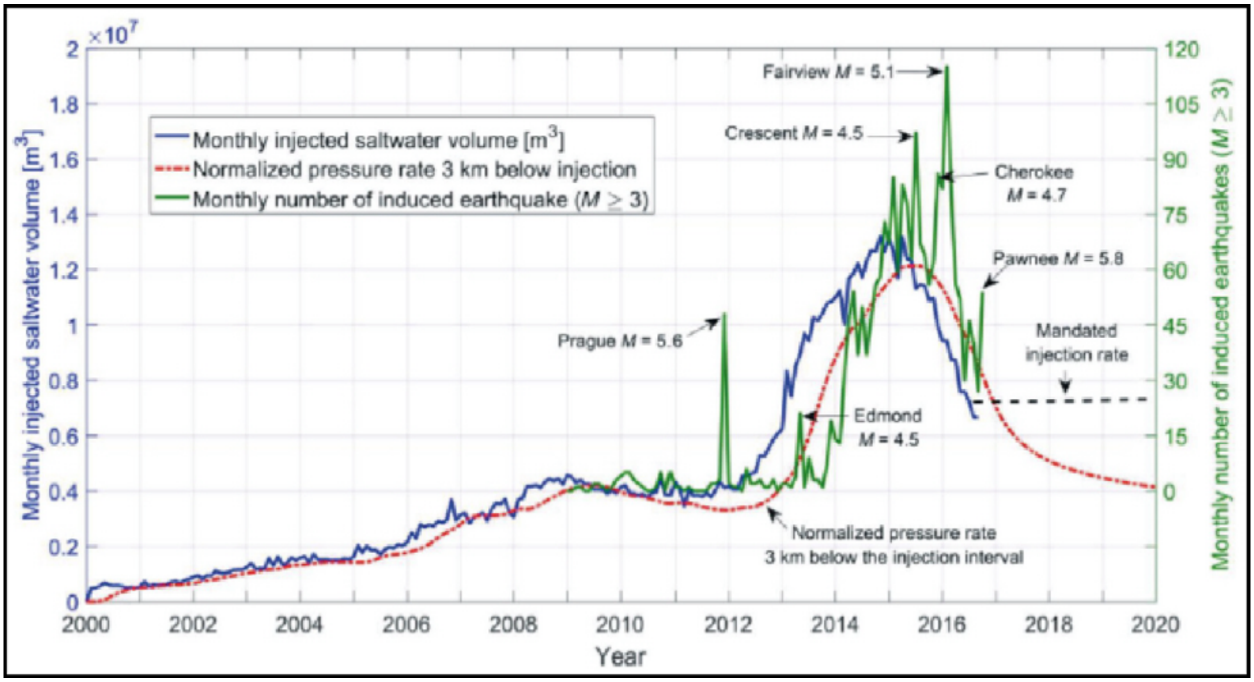
The earthquakes occur at substantial depth, well down into the crystalline basement at about an average of 5.4 km in depth, which is deeper than any oil and gas operations. Earthquakes are episodic and a large earthquake can be followed by a cluster of smaller earthquakes associated with it.

There are three ways to induce seismicity. It's important to note that the energy being released in these earthquakes is tectonic and regional in nature, the result of stress that has built up over millions of years. The release is triggered by human activities. One way earthquakes are induced is by stress of water load in reservoirs.   Lake Mead experienced a magnitude 4 earthquake when it was being filled behind Hoover Dam. In 1975 there was a 5.8 magnitude earthquake, equivalent to the largest magnitude earthquake in Oklahoma, at the Oroville Dam in California. Secondly, earthquakes can be caused by extraction of material and compaction, which leads to stress shifts. An example is in Holland where Shell and Exxon have been extracting gas since the 1960s; in the 1990s the area experienced earthquakes because the extraction resulted in stress changes. Now, models are so sophisticated that the companies can tailor production to minimize the seismicity that they expect. The companies also have a compensation panel that reviews people's complaints relating damage to seismicity, and compensation is made where the connection is shown. The third way to create earthquakes is to change the properties at depth. If enough water is injected to a horizon that has a good communication pathway to a fault that is critically stressed, right on the verge of going, this can increase the water pressure in that fault, thereby reducing the effective normal stress that holds that fault shut and causing slippage. That is the major mechanism that is interpreted for Oklahoma earthquakes. Although the process will never be able to be observed directly, there is a correlation between rising injection and rising seismicity. More important, the converse is also true. Both correlations make a strong case that earthquakes are indeed related to this mechanism of injection.

Injection is going on in the places where seismicity is happening. Large wells equate to more than 500,000 bbls/month and intermediate wells receive 150,000 to 500,000 bbls/month. Smaller wells, 1000 to 10,000 bbls/month, for the most part, are not contributing much to seismic activity. Another factor in earthquake production is the zone of injection. Seventy percent of the water injected in Oklahoma is into the Arbuckle zone, a very thick dolomite shale sequence, in some places several thousand ft thick. It was slightly underpressured, with reasonable porosity and adequate permeability. Oklahoma has been disposing of the brines from oil wells since the 1930s. What didn't happen is injecting as much produced water into the ground as has occurred in the last few years, when it became economic to produce wells that had extremely high water cuts. There were horizontal wells in some plays and a mix of horizontal and vertical in others. Some wells produced more than 10 bbls of water for every bbl of oil, creating large amounts of water to dispose of and ultimately causing the earthquake problem.

Information from 2011 shows that there are some small infrequent earthquakes in two clusters associated with hydraulic fracturing events. The earthquakes appear to have occurred at the same depth as the zones that were being fracked. For more recent frac jobs, earthquakes have occurred at depths deeper than the frac zones, at the basement. The reason is unclear. But most seismicity is not due to fracking, contrary to stories in the news media. report. Some of the Oklahoma press has become fairly competent in reporting and 60 Minutes aired an accurate story. But much of the news media is still trying to tie fracking to earthquakes, and a reason might be because of search engine optimization. If fracking is written into an article, and better yet into the headline, the article is likely to be read many times, which is gratifying to editors. Therefore, the phenomenon will be called fracking-related waste or drilling waste. But this is mostly produced water from the formation, generated during the entire life of the well, long after the well is completed.

In 2015, Stanford completed an exhaustive study of data from the Corporation Commission and concluded the injection/seismicity correlation for three areas in the state. In areas where there was no substantial change in injection, there were no earthquakes. In the south, there was a great amount of injection in the Ardmore area, but it was largely for the purpose of enhanced oil recovery. There was no increase in earthquakes because injection in a water-flood operation cannot be overdone, i.e., there needs to be a balance of what is being added with what is being taken out, and pressures were not changed a great deal. Companies also performed a calculation of how much water was being disposed in these three areas; how many wells were being fracked and approximately how much water was being used in a frac job; and how much water was returning as flow back water. Generally a quarter or a third of the water comes back. The study shows that the quantity of frac water is not responsible for seismicity. Flowback water accounts for about 5 percent of the injected water in the three areas of the state with high earthquake activity.



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The pressure pulse from injection can be observed a surprising distance from the injection site. High injection rate wells in Grant and Alfalfa counties are interpreted to be the cause of 5.1 magnitude earthquake 25 miles away. It is also interpreted to be a pressure pulse rather than the water or water displacement in rocks with very low transmissivities.

While the price of oil was high, there was a large quantity of water being injected into 684 wells drilled into the Arbuckle zone, which sits on the basement. In 2014, the price of oil dropped precipitously, then tapered off. Soon after, injection plateaued and began its own similar decline. By the time a directive came from the Corporation Commission to shut or in reduce the injection in certain wells, much of the reduction had taken place. Companies had begun to find that their wettest wells were sub-economic and shut them in as a response to price. The drop in injection is 1.4 million bbls, about 800,000 of which has now been captured by directives. Last week another directive more or less capped injection at the maximum rate of what was currently being injected. The directive, crafted with an eye to future oil price increases, was to prevent companies from again injecting the amount they were allowed by their permits, which would mean a potential rise in injection of several million bbls/day. Now there is a lock in place to prevent a rise in injection in these wells. Also, the Corporation Commission, which permits these wells, will not grant many new permits to inject into this deep horizon.

For companies that are holding on to permits in these plays in earthquake zones (one is a Mississippian limestone horizontal play with high water cut, mostly in the northern areas, and the Hutton play with relatively high water), many wells have been shut in. Some companies have chosen to plug back their injection wells to a less favorable horizon that is not in contact with the basement. The available data so far indicates this is a reasonable strategy. The only other alternative is to treat the water. The Governor did create a produced water task force, which found the cost to be $2-4/bbl of treated water. A well producing 25 bbls of water for a bbl of oil, at $50/bbl oil, will not be economic. In the future it may pay off for the oil industry to explore the technologies vendors could develop to treat water.

The Corporation Commission strategy has put a stop play in place: if a mag >2.5 earthquake occurs, a company needs to communicate with the commission; with a magnitude 3, there needs to be a pause to work out a remediation plan; with a magnitude 3.5 work must stop for a full 48 hours, and the company must meet with the Corporation Commission to present their remediation plan. Earthquakes can be stopped. There have been two cases where a pause and slight rearrangement of the frack plan have completely shut down the earthquakes.

What is needed for a comprehensive understanding of the situation is an integration of the geology, geophysics, hydrogeology. OGS works with RPSEA. Also, the Governor provided $1 million from the Emergency Management fund.

Data tracking in the underground injection well program was primitive at first. Companies were only required to provide monthly reports every year, which led to delayed interpretation in Oklahoma. Kansas was far ahead in integrating data. Now daily reports are required and the tool that Oklahoma uses is based on that developed by COGCC. The goal is to house all data in a single geo-referenced database.

The seismic activity in Oklahoma may be a harbinger of things to come in the Permian Basin, where some of the plays are very wet and there will be significant water to dispose. Texas has invested in a $4 million seismic network for monitoring.

Comments in response to audience questions.

As fracking uses less water, why does the process cause earthquakes? The reason is not the volume of water in frac wells but rather the elevated pressure.

What was the largest earthquake magnitude associated with fracking? That would be magnitude 3.1 or 3.2, which is small enough not to get too much attention. A problem may be that structural engineers tend to focus on catastrophic damage, ignoring anything below about magnitude 5. There's not much knowledge about damage assessment of a 4.5 or 4.8 magnitude earthquake that causes a crack in a home and then is followed by 40 or 100 magnitude 3 earthquakes that continue to shake that crack until things fall apart. In an anecdote, a seismologist was presenting at a public meeting where earthquakes had caused significant damage to a number of homes. In answer to a question he tried to explain that the data available weren't adequate to define the mechanism. Unfortunately what he said was "We don't have enough earthquakes." It is important to remember your audience.

How much monitoring is required in fracking? The larger independents generally have their own closely spaced arrays that move along with their fracking programs. Smaller operators must monitor the state website.

How many earthquakes are occurring on unmapped faults? The percentage is unknown.

What is the status of produced water? Produced water has original sin. Even if treated to drinking water standards, legally it still is considered produced water. It is not clear if this is a state or federal ruling. The Oklahoma Task Force may address this. Companies in Pennsylvania are treating produced water with a process that drops out organics, then metals, then flash evaporates. The salt is sold for road salt. The water is sold to companies for use in fracking.

What is the cost for reinjections? Transportation is a major cost. For companies that own wells the cost is < $1 /bbl. For 90 percent of water that is injected, the companies own the wells. The remainder are owned by companies that just own and operate disposal wells. Less than .1-.2% of water disposed comes from Kansas, Arkansas, and Colorado. The state does not monitor how much water leaves the state for injection elsewhere.

Why does extraction (of the produced water) not a cause of seismicity? The target zones are in solid Paleozoic rocks. In the Netherlands, extraction occurs in unconsolidated mud, and compaction is a compelling reason for their earthquakes. Earthquakes in some places in Texas may be due to extraction. Los Angeles has soft Miocene sediments. It is not the injection of water that is causing the seismicity but the change in the pore pressure with injection. Porosity is very low, about 10^{-5} in basement; it is easy to transmit that pressure pulse into the basement. Water is being withdrawn from a zone that has no communication with the basement and being injected to a zone that lies on top of basement that is fractured. The pressure head is changed.