Anthropogenic causes of intraplate earthquakes in Oklahoma, USA

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Abstract

Statistical and physical models indicated the evolution of events in the country depends on the human actions. In this analysis, we divided the USA conterminous in three regions seismological active and by Earth's crust thickness variation as Western (25 km), Central (45km) and eastern (~ 25km). Oklahoma is in the mid- continent and the region is one of the thickest crust in the country. In ancient times was supposed to be an inner ocean now covered by the Great Plains. Fracking in this area increasing since 2009 and nowadays more than 4000 wastewater wells are active in the state, most at the Mississippi Lime are in the Oklahoma/ Kansas border. Wastewater disposal wells typically operate for longer duration and inject much more fluid than hydraulic fracturing, making them more likely to induce earthquakes. Enhanced oil recovery, injects fluid into rock layers where oil and gas were extracted, while wastewater injection occurs in never-before- touched rocks and beneath surface areas. This study around Oklahoma pointed out that most of the area located in a former inner sea. In this location most of the fracking occurring with an extraordinary enhancement of earthquakes. Reviewing the entire system, we found that stratigraphy and tectonic may explain the improvement of the events due to the increasing of oil/gas exploration. Injection rate and the total volume of wastewater injected allied to the unknown presence of faults; fractures will trigger earthquakes which magnitude increased. The human action as liquid/ injection, hydraulic fracturing, enhancement of oil recovery, all together will boost earthquakes at a higher rate. The explanation associates the unevenness of the earth's crust and the lack of information for investigators about the earth's structure. The continuity of stress and exploration in the region by humans will rise the magnitude of earthquakes observed since the inner earth's structure is included with an eventual collapse. The last observations pointed out an M6 earthquake and the increasing in depth around Perry with two occurrences one in 2014 (23.2 km) and 2015 (56.2km).

Introduction

Our records showed that earthquakes M ≥4 were a rare occurrence in the middle of USA period 1965-2015. Essentially those events followed patterns near of the known faults like New Madrid. The exception of mid-USA is in Oklahoma/ Kansas border since 2010 there is an enhancement of earthquakes M ≥ 4.5 as well the frequency of such events in the location named as Mississippi Lime. Searching in the records in the period 1950- 2010 only two events recorded, one in 1974 and other in 1997, with the mentioned magnitude. After that time, there was a new occupation by gas/oil companies likely to connect with the observed enhancement of quakes in recent years. There are two reasons those enterprises dismissing researchers in the area, one that is a complicated issue to figure out the exact location of waste water wells are in the region, the other one they arguing that if there were occurrences of small earthquakes observed it would not be a threat to humans. In this study, we focus only on the Oklahoma region considering the following coordinates latitude [37.45N, 33.43S] and longitude [-101.281W, - 93.79E]. Our previous paper showed that the only place mid-continent with the massive presence of earthquakes M ≥4.5 in the period after 2010 is in Oklahoma / Kansas border. To support our hypothesis, we must establish in the locations studied the wastewater wells positions. Also, which of them are operating in conventional and unconventional technics. Unconventional wells are releasing lots of salt water that is discharged underground. The second reason would be the physical mechanism that would allow the increasing number of earthquakes in such region and nothing observed in other locations with a similar number of wastewater wells. The wells data catalog cannot be reliable, since the updates are not frequently, some became withdrawn, inactive, stopped working or just started pumping. Companies do not release a complete information as kind of slant, if it was fractured or not fractured the well, and many had unknown shale formation. The catalogs help to guess how many wastewater wells in the state and to estimate about the disposal of the salt water as a sub-product, as we discussed in a previous paper. [1] For the gas and oil wells data, we used EIA and FRAC FOCUS lately data. At the last moment, we found a Texas map displaying 7,000 wastewater wells and their location in the state. The same was published for Oklahoma that has 3,000 wastewater walls in a smaller area. [11]The data to earthquakes came from three catalogs, two of them with data period1950-2016, and one with historical events. They are USGS, IRIS, and NGDC/NOAA. The catalogs prioritize different kinds of records, and by comparison, it is possible to have an excellent view of each state. [12], [13] USGS was the only source that classified data by depth, magnitude, and included the origin of the earthquake, such as landslide, explosion, and rock bursts. The current theory on intraplate earthquakes suggests that away from plate boundaries, earthquakes often triggered when geological processes, such as the deposition and erosion of surface rock, alter the balance of opposing stresses sub-surface rocks. Change in stress increases of decreases strain - the amount of rock deformation brought about by stress that weakens the stability of faults confined by the stress. Ellsworth [2] agreed the number of earthquakes related to fracking has been on the increase and the industries should monitor them better, it agrees with our observations in locations as Oklahoma as we are going to discuss later. McGarr et al., [3] made a study about the anthropogenic seismicity and described that some regions human-made earthquakes are more obvious because background seismicity is low. Segall, [4]-,[6] proposed that poroelastic stresses be responsible for inducing earthquakes associated with fluid extraction, he presented methods for computing poroelastic stress changes due to fluid extraction for general axisymmetric reservoir geometries. McGarr, [3], [7] studied the maximum magnitude earthquakes induced by fluid injection. He proposed a model to find out how large an earthquake induced by fluid injection or other methods could be. His conclusions pointed that "maximum seismic moments are limited based on the total volume injected in the environs of the induced earthquakes. Earthquakes occurring in spatial and temporal proximity to such operations as hydraulic fracture are immediately under suspicion being triggered or induced. Those papers presented interesting and value ideas on the processes and the influence of unconventional wells or wastewater disposals in the propagation and an increasing number of earthquakes in the regions affected. Nevertheless, it remains a question why in some of the areas with a high number of wells the earthquakes increased and in others it did not, or just happened a greater number of smaller magnitude quakes. Our calculations tried to explain the phenomena physically and somehow to predict the enhancement of earthquake as consequences from the region the wells locations. Clearly, indications pointed out that the boost of earthquakes in the central USA is the result of anthropogenic actions. The first part of this paper shows the local effects of pressure, strain and stress on the brittle rocks, without considering the propagation of shock or pressure waves to fractures. Therefore, to have a better idea about earthquakes propagation is necessary to analysis data not only the physical mechanisms responses limited by environment, space and time. Many physical properties such permeability, viscosity, Young's modulus and thermal conductivity vary with porosity or fluid content in sediments and minerals. The porosity, in turn, depends on the deformation and compaction state and calculated from the compaction curves resulting from the proper compaction modeling. The theory applied to this study the constant stress from the oil/gas companies applied underneath the earth's surface is responsible for triggering earthquakes. The stress enhances the chances to material reach the brittle point the rocks will collapse inducing earthquakes. Particularly, Oklahoma locations are thicker, and the former stratigraphy points out for regions with different material layers, possible with faults and fractures unknown in the epicenter depths for the recent major earthquakes. Various shales composition demand a specific study in the regions intensely exploited to figure out the consequences of drilling. The second part of this study is to isolate the area in Oklahoma/ Kansas border showing the earthquakes with a higher magnitude that happened at the Mississippi Lime and the presence of a cluster of earthquakes M ≥ 4. Cluster earthquakes corroborate the hypothesis that the region collapses and breaks and the rupture points it generates the knots.

Theory

We divided the paper into two parts, a physics explanation about why the earthquakes would happen due to unconventional drilling. The second part of the data and the unusual activity in the Oklahoma/ Kansas area. It is used several catalogs for the earthquakes data it will avoid omissions, duplications or wrongful inclusion in the records. It also includes physics variations, instrument drift, and failure to account for a factor, incomplete data (from one or another catalog), missed data, hidden data, and instabilities on the measures. Oklahoma is partially immersed into the Great Plains. Great Plains are a formation in the middle of USA, partially spread in ten states. They are Montana, North Dakota, South Dakota, Wyoming, Nebraska, Kansas, Colorado, Oklahoma, Texas, and New Mexico, the three Prairie Provinces of Canada (Manitoba, Saskatchewan, and Alberta) and portions of the Northwest Territories. Some writers have used the 100th west meridian as the eastern boundary, but a more precise one is the eastward-facing escarpments—the Balcones Escarpment in the far south and the Missouri Escarpment in the north—that run from Texas to North Dakota, generally somewhat east of the 100th meridian. The formation of this area made by uneven layers of rocks is covering or folding several places wholly or partially. Much of the structure is unknown subsurface structures, and by now, it is impossible to say if is formed by fractures or faults and what depth they happen around these regions. The exploration of oil/gas in the Mississippi Lime region suffered stress during several years by unconventional wells. Many reservoirs are partially empty or have brittle material creating a space weakened by fracking and injecting of contaminated water. Over time, the site collapse causing small, medium, or large earthquakes. The magnitude depends on how long the underground region will be struck for removal of oil or gas, due to the intense exploration in many years now. With unconventional wells, it was possible to reopen for the second and third time several old wells inactive. The material in those old wells yields less tension than the new ones. Many earthquakes happen near of some wellbores, and none happens near others. Here is a clear connection among stress, stress variability, active faults and the permeability of natural fracture systems in the subsurface will add to trigger earthquakes. The physical mechanism for hydraulic fracturing involves injecting a mixture of water, sand, and chemical additives into a subsurface petroleum reservoir at high pressure. The initial stage of a well shows evidence of triggering small earthquakes caused by the strain from the utilized tools that are breaking the rocks to the well's construction. Young's modulus is defined dividing the tensile stress by the extensional strain in the elastic (initial linear) portion of the stress- strain curve:

$$E = \frac{tensile\ stress}{extensional\ strain} \quad [1]$$

$$E = \frac{\sigma}{\varepsilon} \quad [2]$$

Where *E* is Young's modulus (modulus of elasticity), *F* is the force exerted on an object under tension. After some calculation the final result,

$$F = \frac{E\ A_0 \Delta L}{L_0} = kx\ [3]$$

We define $x = \Delta L\ [4]$, and $k = E\frac{A_0}{L_0}$ [5]

A_0 -original cross-sectional area through which the force is applied; ΔL is the amount by which the length of the object changes; L_0 is the initial length of the object. The Young's modulus of a material calculates the force it exerts under specific strain. Young Modulus is directly dependent on the pressure (strain) and brittle material break under an applied pressure. The induced earthquakes will happen at the following stages of the hydraulic fracturing when the pressure exerted increased the strain on the rocks until a rupture point. Our theoretical model supposes a cylinder with walls covered with concrete with a vertical length between 1830 to 3050 m depth. The posterior horizontal length is 2130 m long. Horizontal drilling involves deviating a vertical well bore along a curved path to intersect a reservoir in a near- horizontal plane. The bore is typically around 25-152 mm diameter. Next, explosive charges are placed in the bore and set off to fracture the casing so that gas can get into the bore. In this phase of the process occur the induced earthquakes due to the high pressure on the small horizontal holes. In some cases, the pressure required is 30,000 to 40,000 horsepower that is much energy being consumed. After this process, the fracking wastewater removed and in some cases stored in nearby ponds. Hydraulic fracturing requires many wells, (Frac Focus, 2014). There is where multi-pad hydraulic fracturing wells come in. The number of wells is not all released to the press, then, it is unknown how many of them are in operation or not, by now. The process of each fracking does not consume more than two or three months it is constantly applied high pressure underground every day. The created fracture in the wells, induce small earthquakes, however, it is not the only problem rising. The hydrostatic pressure into the well decreasing because the level of oil and gas declining over time. It depends on from the fluid density (gas or oil), the acceleration of the gravity, and the fluid depth. The process can continue with a second and third recovery stage if the production declines. These operations are probably triggering earthquakes, the shallow depth of most events and the increased magnitude along the years, indicated they are inducing more and more events. The continuing pressure on the same rocks that will be infiltrated with lots of wastewater accelerating the collapse the rocks in the location where is probably some subsurface fractures near the shale or the region of drilling unknown by the companies. The crustal thickness on the USA varies; it is denser mid country in the states covered by the Great Plains. Some evidence pointed out that for layers of material in this location that are not well known. Oklahoma is one of other states in the United States, like Wyoming, Idaho (Northern and West), Colorado, New Mexico around the Rio Grande, Nevada, and Arizona, which have surface irregularities. They are occurring at several different depths making impossible to withstand the stress and tension create by the innovative exploration of gas and oil companies, which are in increasing expansion since 2009. As we mentioned in another study [1] there is not only the drilling that triggers earthquakes in such states. The causes are various, in Oklahoma However, last ten years the majority of biggest events occurred at 5 km depth. For medium quakes, M ≥4 in this stated the epicenter is shallower than 8 km, pointing out an existence of a frail structure underground. Since 2011, scientists trying to figure out a physical mechanism triggering earthquakes by human actions. Finally, in 2016 another major event brought the old question about the anthropogenic reasons for the increasing quakes in Oklahoma and the unconventional wells. Figure (1) shows the events happened in Oklahoma above M3 and the regions with major earthquakes. There is a cluster of quakes near M5 events indicating that nearby the epicenter an extensive collapse of brittle material weakened by the by the modern technics in drilling. Oklahoma has a historical record of increasing number of events in the region between northeastern Oklahoma and central Kansas, incidents in this area started an increase in frequency and magnitude in 2009, in a region named Mississippi Lime. Taking the name apart, the "Mississippian" refers to a geologic period roughly 320 to 360 million years ago. "Lime" refers to marine limestone laid down during the Mississippian when an inland sea covered parts of the North American continent.

The reservoirs.

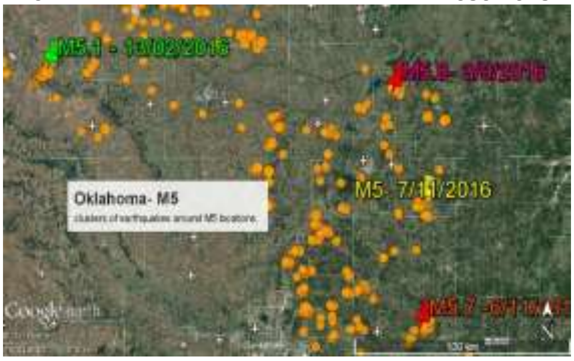

Figure 1- Location of earthquakes M5 and the clusters M3, M4 around each of them.

This thick limestone does diverge slightly from other plays that have a bigger shale component in the context of their interbedded zones. The oil and natural gas play of that name focuses on a specific part of this area centered along the Kansas/Oklahoma border, with some experts estimating it to extend as far as southern Nebraska. While the largest activity has been in northern Oklahoma, areas now considered as part of the shale stretched farther north and west within Kansas. Earlier descriptions put the area of interest at around seven million acres, but with extensions to the north and west, estimates now range to 17 million acres. The play's surface area is similar to that of West Virginia or South Carolina. One of most disturbed areas is in Oklahoma since 2009, the number of earthquakes enhancement in the state seldom had events until 2010 above M4, however, since 2011 the number of events in the same area observed the number and magnitude of earthquake increased.

Historically, Oklahoma had rare occurrence for larger earthquakes and dealing with wastewater injections with deeper wells, up to 1.5 kilometers down, into deeper geologic formations. At those depths naturally occurring faults and if filled with water it will increase the pressure reducing the strength making the faults lines less clamped together. It leads to earthquakes and possible this rare occurrence happened due to fracking. If we are

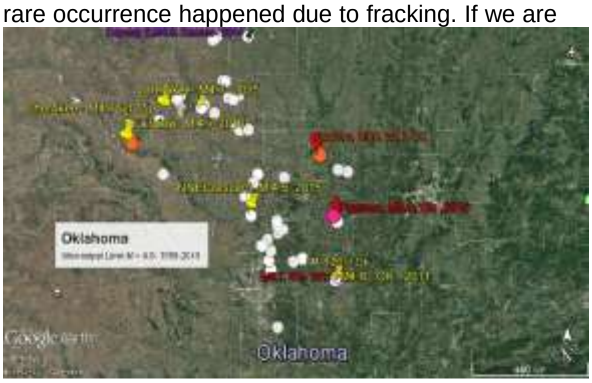

Fig.2 Oklahoma / Kansas quakes in the period 1950-2016, M ≥ 4. Observe clusters of medium magnitude earthquakes at the Mississippi Lime

The entire play is huge, encompassing 30 million acres and more than thousand wells drilled in 2013. The top of Mississippi is a major erosional unconformity across Kansas. These 'chart' reservoirs are widespread, a variation of thickness from few meters to 25 m thick and heterogeneous in nature. Partially caused by uplift alteration, erosion or deposition of the original limestone commonly referred as Mississippi Lime. The figure (2) shows the strongest earthquakes happened in Oklahoma one 2011 magnitude 5.7 at the depth5.2 km and the other on in 2016 in Pawnee, M 5.8, depth 5.6 km.

Figure (3) displays the entire USA and the abnormal variations in the thickness of the crustal surface on the country. Although ten states are under the Great Plains, Oklahoma and some others are not totally included in the area. The old Appalachian Mountains present a highland area in the eastern part of the continent, while the younger Rocky Mountains form a higher more rugged frame in the west. Between the two are the lower, flatter physiographic provinces: the Canadian Shield, the interior plains, and the Great Plains. The picture is showing and idea how the crustal thickness is acting in the USA. Higher thickness is situated in the middle country, 45 km or more. It looks like the thickness moving from West to East with the thicker surface in the middle. Clearly, there is a relationship link magnitude of

narrowing the coordinates on Mississippi Lime, [40.21N, 33.54S, -94.02 E, -98.51W] the larger earthquakes were happening in Shawnee area or nearby. Examining the Oklahoma state during fifty years and with more details since 2009, the accumulation point for earthquakes with Magnitudes 4-6 are most on the Mississippi lime, it is clearly a cluster of earthquakes in the region Oklahoma / Kansas, where the is located the highest powerful quakes in the central continent. The region was transformed through uplifting erosion and exposure to weathering and other geologic processes all before buried again in subsequent periods. Due to its brittle nature, the 'chat' has served as a reservoir rock, and its weakness makes it fragile for the stress and pressure applied in the region. Our calculations observed that contemporary events in the area happened most at depths 0- 7 km it point out for a possibility of subsurface faults, fractures in the area.

earthquakes and crustal surface apparently the higher magnitude. Let us remind the tectonic geomorphology on the continent. The Western side is a boundary of the tectonic plate convergent, with a late Cenozoic rifting orogeny. Near the Pacific Ocean, the crustal thickness is thinner as 15 km. A Mesozoic orogeny formation divided the feature from a Platform created by late glaciers. At the eastern side, Platform makes boundaries with several different formations shield, Paleozoic orogeny, Coastal Plain and a Continental margin.

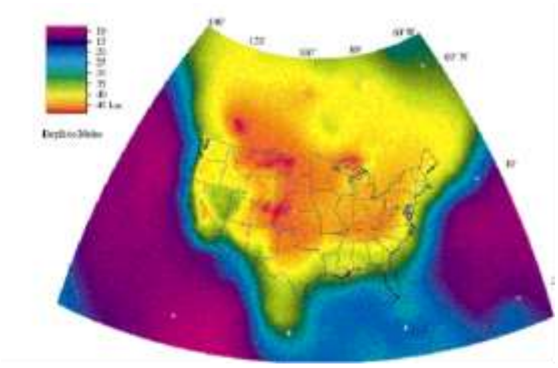

Fig.3 - This figure shows the Earth's crustal thickness in North America. The middle country is thicker than other regions. It is also the location of Great Plains. (Published under permission by Sandvol et al. [9])

Our study found that locations with higher crust thickness generating lower magnitude events, small earthquakes have increased numerically in specific areas presenting swarm events. Without anthropogenic actions would be rare happening earthquakes intraplate in the USA. The most dramatic event was the one occurred in New Madrid fault in 1811-1812, magnitude 7.5. Small earthquakes are increasing in frequency and magnitude after advanced technologies applied to mines, wells and, some underground nuclear tests.The figure (3) shows the crustal thickness in North America recently released due to the source of data. It indicates that the Earth's crust is uneven in the US, some locations are extremely thick and some thinner, the variation is roughly 25km- 45km- 25km, from west to east, Midcontinent is roughly 45 km. The importance of the crust relies on the fact thicker place receive a response with low quake activity than the thinner ones. Mississippi Lime in Oklahoma is supposed to be thinner than most of the state, therefore, is more susceptible to happen earthquakes than places thicker; also, there is a possibility that Mississippi Lime is a transition zone thinner than the rest of the state. It would mean subsurface fractures or faults in the region, could also be involving material more sensitive for the intense exploration in the location.

Results

This research proposes a theory based on the Young modulus and the force applied in a particular region, for many years, which causes a collapse in the area due to the weakening of the material under tension. The brittle material triggers earthquakes, in clusters and increasing magnitude. We also observed a number variation of earthquakes versus location what drove us in the crustal thickness influence in the enhancement of events. Results showed us that the three most important regions of the country presented clusters of small and medium earthquakes. We limited our study for earthquakes M ≥ 3 since the number and frequency of smaller earthquakes makes a proper analysis difficult. The study on the wells based on the reports from Frac Focus. [11] The study of earthquakes is in the several catalogs available online. [12], [13], [14], [15]

The formation of middle US created several scenarios as unfolded and folded structures, unconformities as subsurface fractures and faults were hidden and unidentified so far. Some regions as Oklahoma have subsurface faults or fractures that under intense strain from the directional wells break or move creating the small events observed. A brief analysis of regions that increased seismicity last few years provided the following conclusions: a) before 2009, the regions targeted had no history or lower seismicity. b) Magnitude and depth of quakes are low in those 'new' locations. However, places surrounded by preexistent faults like New Madrid the shakes presented a more profound depth and higher magnitude. c) Regions with enhancement in seismicity last years presented clusters or swarms of intermittent earthquakes with M ≥3.Some areas have quakes reaching M≥4 even though, previously it was no event in the area. d) Susceptible areas to present a major number of small or medium quakes in overall share a general composition of black, organic-marine formation in the mid-US. Finally, the water injected into the ground have two physical effects, one it increases the pressure underground surface faults another is the strain effect in the material underground. Because of the discrepancies in the Earth's crust thickness, under stress, the location responds with different intensity and magnitude. Therefore, two reasons explain why some places with wastewater wells have low earthquake activity, one is the volume and pressure applied to the injection, the second one is how thick the crust is in this area and what material is in the composition. Nowadays, the information about wastewater wells is incomplete. However, we know that places where is methane gas exploration as Virginia, Colorado, California and Wyoming ones must drill deeper wells up to inject water, and it provokes earthquakes with lower or higher magnitude depending on the thickness of Earth's crust in the location. The formation, depth, and thickness of the deposits in each site exploited makes individual wells reply in a unique way to seismological stress. About the catalogs, there are discrepancies between the numbers of events, the sets rarely matches with each other in the period of one year. In the period 2009-2015, only one year USGS reported a higher number of documented events than IRIS (2010). They remained with different quantities on 2015. The data categorized as anthropogenic or various sources start unclassified and released, by USGS some years ago. Iris usually recorded small earthquakes with depth zero, but USGS. Iris does not distinguish anthropogenic sources. However, it reports earthquakes with depth zero, although it is not possible they do not distinguish natural from unnatural events as USGS does, sometimes. The estimative of events between 1- 4 magnitudes showed that in California and Oklahoma for some years had a similar number of recorded seismological disturbances. However, California has some faults, fractures, and other formations well studied and where quakes normally occur. Oklahoma did not have a history of events M4 until 2009. Also, no events until 2000. The reports indicated that the number of wells decreased in 2014 and the frequency of earthquakes increased.We again remind that these reports had inaccuracies due the delay for the companies in releasing updated information. The causes of the enhancement of the events are tightly attached for the extreme and increase fracking in the Mississippi Lime area and the unconformities of the crustal surface in this particular location. The two biggest earthquakes in Oklahoma in 2011 and 2016 with magnitudes 5.7 and 5.8 happened in this region, which had few stories of large earthquakes. Since 2009, those places added to waste water wells due the exploitation gas and oil that needed to dispose of the wastewater that will be deposed in deepest wells into geological formations. The method increases pressure underground and depending on the material, and thickness of the crust in the region will lead to earthquakes. Those quakes are not necessarily close to the wells depending on what disturbance the injection makes bellow the ground. The crustal thickness is the most important factor in events. The middle continent has different thickness points with various shale formations. It explains the often earthquakes in some regions of the country and few in others. The models must deal with variables as depth, magnitude, location, however, is necessary a know the composition of each shale elements as the porosity, permeability, density of the oil, gas or coal, dissimilarities in the thickness. Finally the dimensions of the reservoir.

Unconventional wells, which are associated with wastewater wells, are greatly responsible for increasing of small and medium earthquakes special in areas as Mississippi Lime in Oklahoma.

The priority of our research it was to investigate the enhancement of earthquakes intraplate and possible relationships with any wells (known slant) for oil and gas or wastewater disposal wells in the US. Unfortunately, there is no available catalog for the wastewater disposal wells in the country. Some states reported wastewater wells and the location but not all of them. Recently Oklahoma released a map with the locations of wastewater wells and earthquakes; both maps did not match. It means from the 3000 wells constructed the earthquakes rise near some of them but in some places were uneventful. Possibly, it indicates that the highest activity mid-continent last eight years has anthropogenic interference with partial connection with the drilling, the substructure into the ground is also important.

Conclusions

The ascending construction of unconventional wells in Oklahoma in the region known as 'chat' or Mississippi Lime had increased the possibility of earthquakes of magnitude M> 5 since 2011 when the first occurred. Fracking not only enhances the number of seismological occurrences and the waste produced and used must be contested in its polluting infrastructure**.** In California is documented that oil wastewater is being used to irrigate crops for some of the largest food brands.

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