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# INDUCED EARTHQUAKES CORRELATIONS WITH EARTH'S CRUSTAL THICKNESS

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**ABSTRACT:** In this paper, we carried out an investigation about the possible causes for enhancement of earthquakes in USA over the last seven years. From our calculations, indications set forth that the increased evolution of the quakes in the country is due to the human actions. For further analysis, we divided the country into three main seismological regions: western, central and, eastern. We roughly classified the areas by their thickness of Earth's crust in a variation 25-45-25 km. The thickest area is in the mid- continent and most of this region are part of the Great Plains. In our study, we are going to investigate the reason for the Mississippi Lime in Oklahoma a very thick area, started an unusual earthquake activity since 2010, most at Oklahoma/ Kansas border. In this region, also, there are many anthropogenic activities concerning with the waste water wells and more than 4000 of them active at the moment in the state. The enhancement of earthquakes cluster is investigated in other locations in the USA. Those studies elsewhere indicated that the anthropogenic reasons vary; one of the most important is the deep waste water disposal used to recycle contaminated water extracted from the gas and oil wells, and other independent sources will be examined. We intend to explain why not all the waste wells are triggering earthquakes and how it would be strongly attached to the unevenness of the Earth's crust.

*Keywords: Earth's crust, waste wells, Oklahoma*

## 1. INTRODUCTION

There are many ideas and speculations on why intraplate events occur, but no consensus has emerged on how they are generated or how they continue to occur over many earthquake cycles. Intraplate earthquakes also present significant seismic hazards, especially because they can affect densely populated regions with little preparation for seismic shaking. The existence of intraplate earthquakes remains a deep scientific mystery with strong social implications that needs to be solved by innovative approaches. In this paper we are trying to explain how intraplate earthquakes are associated with the thickness of the earth's crust, and how the manmade earthquakes would represent a threat for the society.

Ellsworth [1] agreed the number of earthquakes related to fracking has been increased 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., [2] made a study about the anthropogenic seismicity and described that in some regions manmade earthquakes are more obvious because background seismicity is low. Our research find out that places as the midcontinent are easier to checkout human activity than California coast.

Scientists [3] speculated that wastewater wells could be responsible for creating a wave of pressure that crawled through the subsurface and triggered the earthquakes far from the wells, some as far as 35 kilometers away. Wastewater can result from a variety of processes, including those related to energy production. For example, water is usually present in rock formations containing oil and gas and therefore will be co-produced during oil and gas production. Wastewater can also occur as flow back from hydraulic fracturing operations that involve injecting water under high pressure into a rock formation to stimulate the movement of oil and gas to a well for production.

Wastewater injection increases the underground pore pressure, which may, in effect, lubricate nearby faults thereby weakening them. If the pore pressure increases enough, the weakened fault will slip, releasing stored tectonic stress in the form of an earthquake. Even faults that have not moved in millions of years can be made to slip and cause an earthquake if conditions underground are appropriate. Although the disposal process has the potential to trigger earthquakes, not every wastewater disposal well produces earthquakes. In fact, very few of the more than 30,000 wells designed for this purpose appear to cause earthquakes. In this paper, we investigated why and where the disposal wells would trigger earthquakes.

## 2. RESULTS

Our registers showed earthquakes with magnitude $\geq 4$ are a rare occurrence on the middle of USA covering the period 1965- 2015. Those rare events happened most near the known fault as

New Madrid. One exception is in Oklahoma/ Kansas border which since 2010 has shown an increase of seismological events on the Mississippi Lime and the following characteristics magnitude ≥ 4 and depth ≤ 5. Once this pattern on Oklahoma was delineated by our maps it needed more clarification and research so we narrowed our period of search to 2009- 2015. There were two reasons to collected the information on this period, one it is an implement of great number of waste water wells injection in the country and other the excellent records at the same interval in USA, about earthquakes.

The Fig.1 shows the earthquakes events in Oklahoma / Kansas last seven years. The quake activity in this region was observed during last fifty years with more details since 2009, and it was notice an accumulation point or a cluster of earthquakes last years with Magnitudes 4-6 which happened most on the Mississippi lime, the exact location is at the border region Oklahoma/ Kansas determining the highest activity in the middle continent, sometimes above California. Historically this region was transformed through uplifting erosion and exposure to weathering and other geologic processes all before being buried again in subsequent periods. This place is called 'Chat' has served as a reservoir rock and its weakness make it fragile for the stress and pressure applied in the region. Events on the area happened most at depth 0-7 km and the same depth remarks occurred in other states analyzed. It is a possibility of subsurface faults, fractures in this region. Wells there produces lots of water; produced water is many times saltier than ocean water. It also can contain toxic metals and radioactive substances. Water disposal underground is the most inexpensive solution; other treatment methods would costs much more.

The uncommon activity in the region points out a discrepancy for others places in the middle country. In order to better understand for the location we defined a central region with the following coordinates 37.87N, 33.60S,-94.52E,-102.95 W, and considered only earthquakes with magnitude ≥ 4. Before 2000 the region did not assist any earthquake above magnitude 3 however, the frequency and the magnitude has been increase last seven years. We also search for the number of wells conventional and unconventional opened in this location and they have decreased last two years. Even though the number of waste water wells is now, 3,000 wells distributed on all the state, the earthquakes happened preferably in Mississippi lime region**.** This location has many conventional and unconventional wells since 2007 and waste water wells since 2009. It is a thick limestone section differing slightly from other plays and have a bigger shale component as part 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 oil 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 extension to the north and west, estimates now rage to 17 million acres. This area in Oklahoma is one of the most disturbed since 2009 when the number of earthquakes started to increase.

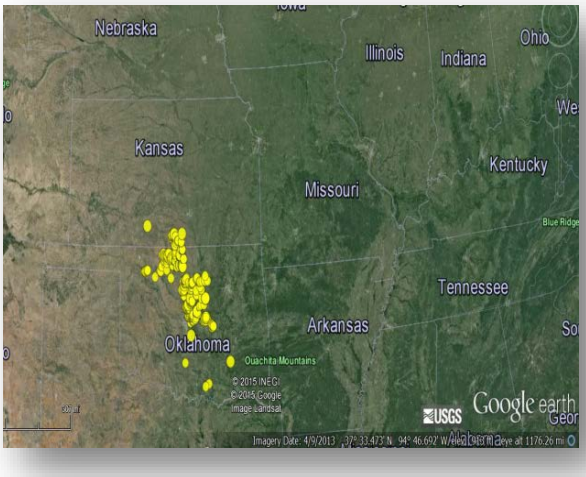


Figure 1 - Earthquakes with magnitude equal or above 4 in the period 2009-2015 in the Oklahoma/Kansas region.

Waste water wells disposal started around 2009 in Oklahoma. In 2011 an earthquake happened in the area with magnitude, 5.7 and depth around 5 km, reminding that depth ≤ 5km is one of the characteristics in what we understood as an induced earthquake in some areas midcontinent. At that time it was dismissed as connected with the injection wells by scientists and by oil/ gas companies.

In Virginia, also in 2011, an earthquake which caused much of damage in the area occurred with magnitude 5.7 in the Richmond basin which is far from the Marcellus shale coincident with an introduction in 2010 of a new technic to exploit coal bed methane that especially in that area is very hard and explosive. Coal bed methane is a natural gas trapped in the seams of coal deposits, and when it is sucked from the earth it brings up enormous amount of water with salt and it can't be legally disposed on the ground surface. Therefore it is drilled in deeper wells, up to 1,5 kilometers down injecting the water into deeper geologic formations.

At those depths you have natural occurring faults. You put water there increases the pressure, reduces the strength and makes the fault lines clamped together. Also depending on the rocks formation it could increase the probability of the brittle material under strain break under the applied pressure near the faults. This pressure is directly dependent of the Young's modulus (modulus of elasticity) and varies for different materials under strain. Coal beds in the Triassic Basin near Richmond and Farmville were formed 205 to 245 million years ago, when Pangea was splitting up rather than colliding. In the Triassic Basin, pressure to convert organic plant material into coal came from just the weight of overlying sediments, without tectonic squeezing - that is why the Chesterfield County coal is bituminous, rather than semi-anthracite.

The area of our interest is located is located at north of Richmond and extends across the Virginia coastal Plain in the tide water region of the state, it is Taylorsville basin. Since 2009 studies indicated that could contain as much as 1,6 trillion cubic feet of natural gas. At this time they introduced a new technic in the area known as micro wave fracking since the production have decreased with conventional wells. Both areas, Oklahoma and Virginia were dealing with the waste water wells, at the time and it is possible that the big earthquakes were due to that.

In our other paper [4], we also discussed the mechanism for hydraulic fracturing which involves to injecting mixture of water, sand and chemical additives into a subsurface petroleum reservoir at high pressure. The initial stage of a well shows small earthquakes caused by the strain to break the rocks to construct the well. However, each place pursue different geological formation, it means that some are harder to break as the coal bed methane in Virginia, and the stress-strain on the rocks will be much higher than for example, the one used to exploit marine limestone in Oklahoma. The Young modulus varies for each material under pressure, therefore it will be more damage depending how brittle is the material under pressure. Then, for each geological formation a different pattern for earthquakes will be delineated. The crustal thickness on USA varies is denser in the mid - continent in the ten states were covered by the Great Plains. Apparently it is the reason because the mid-continent has smaller earthquakes with some exceptions nearby known faults. The second conclusion will be the thinner crust will cause higher magnitude and more frequent earthquakes. Figure 2 showing the Earth's crust variations in USA.

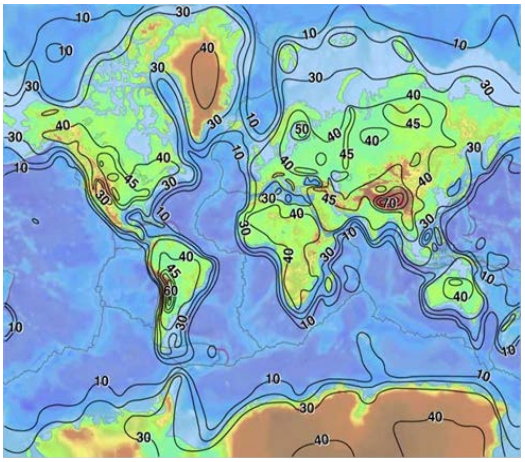

Figure 2- This contour map of the thickness of the Earth's crust was developed from the CRUST 5.1 model. The contour interval is 10 km; we also include the 45 km contour for greater detail on the continents. [7]

Observe that midcontinent is thicker as 45 km and greatly varies at the Western side near the Pacific coast where it is thinner as 25 km. In our previous study we found out that the thickness of the crust is the most important factor in the surge of earthquakes in different locations since the crust is uneven in all the continent with variations between 20 -45 km in the midcontinent being less thick at the Western and Eastern boundaries. Our study considered not only those two events, but also the researching on the enhancement of quakes in other points of USA, obeying the magnitude $\geq 3.5$. From these studies the USA response for events allowed to divide the country in three main regions seismically active. The central region formed by most of states in the Great Plains, west and eastern sides. The three areas presented diverse geological formation, implying varied earthquakes characteristics. The period comprehended 2009-2015 showed that the Western side near of San Andreas Fault earthquakes $M \geq 7.0$ was not uncommon. However, in the Central and Eastern side seldom times earthquakes were $M \geq 5.0$ The western side has a history of higher quake activity partially because is the boundary of two tectonic plates , formed by subduction zones, faults known and unknown , fractures and a thinner crust. The Central part is very thick sometimes reaching 45 km, and events has lower magnitude. The eastern side has a complicated geological history mixing thicker and thinner places, younger and older crust, the magnitude of earthquakes is not higher than M 6.0; however the intensity of earthquakes at eastern side is much more destructive than the western with the same magnitude. Recently Hennings et al. [5] discussed the relationship between stress, stress

heterogeneity, and the permeability of subsurface fractures and faults. They analyzed a Sumatra region, Indonesia. They find out that reservoir potential is most enhanced in areas with large numbers of fractures with high ratios of shear to normal stress. This occurs in areas of the field that are in strike-slip stress style. Comparatively, reservoir potential is lower in areas of the field that are in a thrust- fault stress style where fewer fractures with high shear- to - normal stress ratios exist. Working on this direction we find out that many earthquakes happen near of some wellbores, and none happened near others. Therefore, it showed a clear connection between stress, stress variability, active faults, and the permeability of natural fracture systems in the subsurface. An extensive analysis in other USA states showed that the enhancement of earthquakes were most observed in the central part of the country as indicating non natural causes. Even though the other localities would have a small enhancement would be harder to detect those events as unnatural. At the New Madrid seismic zone small earthquakes with magnitudes between M2 and M4 increased last seven years with a special increase in 2011which source we could not find. As a following research we studied Arkansas because is a state part of New Madrid fault system. In the first period analyzed 1965-2008 there were only 3 medium events in this area $M \geq 3$ by year. After 2009 small and medium earthquakes increased. A location Greenbrier/Guy where 160 earthquakes happened between small, medium magnitudes with depths 0- 10km.This location has a minor Greenbrier fault nearby earthquakes swarm location. There is also a great number of waste water wells disposal due the coalbed methane wells.

The next location is Colorado in the period 1965-2009 the events started to be recorded in 1973 with an explosion reported in East Tavputs Plateau, unknown origin. A location of Paonia experiment a swarm of earthquakes reported as rock burst; the first detection officially was reported in 2001 in the West Elk Mountain. Since 2009 there is an enhancement earthquakes clusters due to the rock burst those are all small earthquakes. Other point in Colorado with rise of occurrences is located in Trinidad, near Sangre de Cristo Mountain. Trinidad is situated on Raton Basin, at the foothills of the Rocky Mountain. Colorado also is part of the four corner region, the larger US methane anomaly, and highly methane exploration is being done. Several waste water disposals are located there. The sedimentary beds are Paleozoic, Mesozoic, and Paleogene age. The eastern part of the basin, the sedimentary section is covered by flours of basalt of Miocene age as observed in Richmond, Virginia. Those two locations in Colorado had an increase activity due not only for the waste water disposal wells, but the heavy coal bed exploration. [6]

Texas had three important regions with the increasing of earthquakes one was in Dallas observed since 2009, the main characteristic of those earthquakes is the depth location reported as 5 km. In 2015 it is reported some events with depth $\geq$ 8 km. The activity is possible attached for a higher number of unconventional wells in the region. However, the magnitude of those events did not surpass M4. In 2015, there were 50,000 waste water wells in Texas. Only one earthquake above M4 was reported in Dallas, in 1999. The place is a stage of increasing small earthquakes but they are not above M4, in this location is a rare occurrence, and the depths are shallow, seldom times the depth is above 5 km. The other point targeted for earthquakes is San Antonio all them at 5 km depth, in the period 2009-2015. In 2011 the place was stroked by a magnitude 4.8. Still working on Texas State, there was another cluster of earthquakes located in Snyder. It was discovered some years ago a new shale in Snyder called Cline shale, it is a Permian basin comprised of three parts: the eastern Midland Basin, the central basin Platform and the western Delaware basin. This area is covered by black shale, organic -rich, deep water materials that would become source rocks in later geologic intervals this material is similar as the Mississippi lime reported in Oklahoma. It is supposed to be an enormous reservoir and they are preparing a heavy hydraulic fracking next years. The records provided about 57 small earthquakes up to a depth 7km. In this particular area of Texas, the events had increased 2010- 2014. All in all, there are 50,000 waste water wells officially reported in Texas and it covers most of the state. However, the quakes activity was observed more into the three areas Dallas, San Antonio, and Snyder. Finalizing our analysis states near New Madrid fault, Arkansas, Missouri and Tennessee, displayed a pattern with cluster of small earthquakes with epicenter bellow 8 km with small and medium magnitudes. Other States further was of New Madrid had different characteristics happened in cluster as well, but shallower depth (0-5 km).

The formation of middle US created diverse scenarios as unfolded and folded structures, unconformities as sub surface fractures and faults hided 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. The analysis on the increased seismicity last few years provided the following results:

a) Prior 2009, the regions targeted had no history or minor seismicity. b) Magnitude of earthquakes middle of USA had seldom cases of M ≥ 5 therefore; these earthquakes also occur in shallower depths most 0-5 km. On the other hand events near New Madrid fault for example even though rarely happen with M ≥ 5, are able to have profounder depth.

c) Regions with enhancement in seismicity last years presented clusters or swarms of intermittent earthquakes with M ≥3. Some regions have quakes reaching M≥4 when previously it was no event in the area. d) Susceptible areas to present major number of small or medium quakes in general share a general composition of black, organic- marine formation in the mid-US. e) The contaminated water injected underground under high pressure has a strain effect in the materials underground and depending of the nature of the material reached it will ignite earthquakes in subsurface faults. Because the discrepancies in the Earth's crust thickness, under stress different locations will provide diverse intensity, magnitude and depth event. Therefore, three reasons will explain why some places with waste water wells have low earthquake activity, one is the volume and pressure applied to the injection, the second one which material injection water will reach and the third on is how thick the crust is in this area. One last reason or cause it would be the presence of subsurface faults or fractures unknown. Nowadays, information about waste water wells locations are incomplete, we guess that the contaminated, salty water released by methane gas exploration has a first cheaper discharge the drill of deeper wells near the gas exploration sites as Virginia, Oklahoma, Colorado, California and Wyoming. Those wells are the first responders for the increasing of earthquakes in those states.

On the western side is harder to distinguish the origin of earthquake unless having instruments that would supply some extra data providing the source quakes as natural or unnatural. Therefore analysis to the western side (California) of country has provided partial data.

The eastern side has a complicated geological history and contributes with larger earthquake events, seldom times. However, for the explained before earthquakes at the eastern side are more destructive in nature than in the western.

The formation, depth and thickness as the deposits in each location exploited make an individual well replies in a unique way to seismological stress. Our analysis on USA showed an enhancement of small magnitude earthquakes over the entire land. Many states presented locations with swarm of small earthquakes with different magnitudes. So far, there are magnitudes most in the range M3 - M4. The exception it is the western where the earthquakes reach magnitudes ≥ 4, easily.

About the catalogues investigated and used in this research there were 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 higher number of documented events than IRIS (2010). They remained with different quantities on 2015. The data categorized as anthropogenic or different sources started to be classified and released, by USGS two years ago. On the other hand, several small earthquakes with depth zero were not reported by USGS, only IRIS had all of them recorded, though IRIS is unable to distinguish anthropogenic sources. Both catalog provided that small events magnitudes 0-3 in 2009 were a total of 2145 in average covered California. In 2014 this number has increased to approximately 5340 events, with a leadership of Oklahoma and second California. Oklahoma showed a bizarre behavior in 2009 no event M ≥ 4, however in 2014 the number suddenly is 22 events, last seven years earthquakes magnitude ≥ 4 are becoming common in Oklahoma. Apparently everything indicates that this increase in the Mississippi lime area is due to the unconformities of the crustal surface at this particular location. In this study we mentioned two earthquakes Oklahoma, Virginia both with M5.7 both happened in 2011. In the region they occurred has unfrequently stories of large earthquakes. However, since 2009 those places added waste water wells due the exploitation of coal bed methane that needed to dispose the waste water that will be deposed in deeper wells in geological formations. However, this method increases the pressure underground, and depending the thickness of the Earth's crust in the region, as well the material of rocks will lead to earthquakes. Those quakes are not necessarily close to the wells depending of what disturbance the injection makes bellow the ground. A physical model that would input data and variables, as pressure, Young module, and also considerate the presence of faults are impossible nowadays some of those faults are unknown. We are also dealing with different kind of shale material, porosity, permeability, density of oil , gas or coal , dissimilar thickness of crustal surface , such factors play different rules on the hazard events observed and compiled. Unconventional wells close associated with waste water wells, are greatly responsible in the increase of small and medium earthquakes in some specific area in the midcontinent. However states that reported to not have wells experimented an

increase of small superficial /shallower earthquakes as Georgia and Maine. Nevertheless, Georgia reported some waste water wells in their territory, some years ago. Besides those facts there is also big events that are manmade as in Nevada during the period 1970-1980 or more recently due to nuclear explosions. After 2000, Nevada earthquakes M≥ 5 are a very rare occurrence; although at the moment the western side of Nevada has an enhancement of events, probably associated with waste water injection.

## 3. DISCUSSION

The causes of the enhancement of small/ medium earthquakes during the period 2009-2014 in USA were due to different human activities. How those actions influence the ground and will respond to these interferences is dependent most of the thickness of the earth's crust in the region analyzed. The presence of the subsurface faults or fractures dormant or half active also will change the increase in magnitude and the frequency of events. The western side contributes with the highest level of magnitude, during the period observed. California contributed with the events M ≥ 6, the biggest events observed thirty years ago in Nevada were nuclear experiments, nowadays west side of Nevada showing cluster M ≥ 4, not totally identified by human activity so far. The western side of USA is the thinnest and younger geological region with some places reaching less than 25 km; therefore events powerfully increase in these locations. Central part of USA is the thickest one, around 45 km, and also more stable geological formations, the reason for the exception active Oklahoma / Kansas relays in the awaken subsurface fractures due to the human activity.

## 4. CONCLUSION

The main issue on our research was to investigate the enhancement of earthquakes intraplate and the possible causes and sources for that. Our conclusion it was that waste water disposal wells in the country the ones known as deeper disposal wells are responsible for this increase. Unfortunately, there is no available catalog for the waste water disposal wells in the country. Some states reported waste water wells and the location but not all of them. Oklahoma recently released a map with waste water wells and earthquakes, both maps did not match, it meant from the 3,000 wells constructed earthquakes happened near some of them and some place were uneventful. We found out that most of the higher activity middle continent area occurred last seven years was anthropogenic interference and sometimes partially connected with drilling.

Many places presented the events in clusters in different scenarios, and far from drilling places in varied areas of the country; most of them have been clear attachment with waste water wells. The most important factor to earthquakes it is the thickness of the Earth's crust, places thicker has less events, than locations thinner. The midcontinent is thicker than western edge; therefore there are fewer occurrences of earthquakes and smaller magnitudes in the central region. The eastern side has an uneven structure in the Earth's crust however at contrary of western side is far from the border of a tectonic plate, therefore events rise smaller magnitudes than the western side. Events look connected most to waste water wells used for coal bed methane and oil, mining, and nuclear explosions; some events were not reported by both catalogues, many places showed superficial quakes in a depth 0-1km, those events are mostly small magnitudes varying 1 ≤M ≤ 3.

The dependence between magnitude and depth of earthquakes rely on the ground thickness, thinner ground will create larger magnitude quakes, the distribution of crust thickness in US is the follow it is thicker in the middle, thinner in the western, and variable at eastern. At western side magnitudes usually reach M ≥ 7, in the middle of country and eastern seldom times will be M ≥ 5, the exception would be New Madrid, and Charleston. As a final point, the Oklahoma/Kansas activity experimented last period 2009- 2014 most at the depth 0-5 km with medium magnitude ( M≥ 3.5) indicates that there is an unknown subsurface fractures in a region identified as Mississippi Lime, called as the Chat. This region is similar for the one observed in Arkansas (with similar earthquakes swarm, M≥3.5) nearby New Madrid fault.

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