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Seismicity Spikes and Earthquakes in Oklahoma: 2009-Present

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Abstract

Since 2009 the state of Oklahoma has experienced seismicity spikes pushing yearly totals of significant earthquakes from around 2 per year (in years prior) into the hundreds. The purpose of this paper is to present the history of Oklahoma's problem with seismicity spikes, the science around the issue, and the governmental approaches to solving the problem. Experts in the field of seismology and geophysics have arrived at a consensus regarding induced seismicity in Oklahoma, but regulating associated industrial activity is an on-going political hot topic on which representatives and the public are divided. This project examines the regulatory approach of the Oklahoma Corporation Commission in managing the state's seismicity spikes and mitigating Oklahoma's earthquake hazards going forward. As well, the project presents scholarship related to induced seismicity, policy options available to regulatory bodies, and the complicated relationships between different industrial activities and varying levels of seismic activity. Generally, the most hazardous induced seismicity in Oklahoma has been strongly connected to wastewater injection, which has been the primary focus of regulation by the OCC in recent years. However, the commission's seismicity response has been gradual, and may be troubled.

Introduction

The El Reno Earthquake

On Wednesday, April 9, 1952, the city of El Reno, Oklahoma experienced a historic event: a record-setting magnitude 5.5 earthquake. This was to date the greatest earthquake recorded in the state's history, and while it was not an *especially* expensive earthquake in terms of damages, it was reportedly felt in neighboring states, and, most notably, it held the record for more than five decades afterward.[1]

A Brief Introduction to Earthquake Categorization

The most well-known seismic magnitude scale is the Richter Magnitude Scale (referred to as the Richter Scale here forward), based on a logarithmic formula developed by Charles Richter in the 1930s. On the Richter Scale, the magnitude value is represented in terms of whole integers and tenths (one decimal place). For example, the aforementioned 1952 El Reno earthquake was recorded as a 5.5 on the Richter Scale. Richter's formula is derived primarily from the amplitude of waves recorded by on-site seismographs during activity and has been adjusted and tuned over the years. Other scales (such as moment magnitude and surface-wave) are designed to align fairly closely to Richter's; categorizations are as follows:

Category:	Magnitude:
Micro	1.0-1.9
Minor	2.0-3.9
Light	4.0-4.9
Moderate	5.0-5.9
Strong	6.0-6.9
Major	7.0-7.9
Great	8.0+

[1] More information on the story around the 1952 El Reno earthquake can be found in a piece published by *NewsOK.com*, an arm of *The Oklahoman* newspaper*:* Allen, Sally. (2004, February 25). Oklahoma Shakedown: The 1952 Earthquake. *NewsOK.com.* Retrieved from: http://newsok.com/article/1184414.

Note that because the formula is logarithmic, an earthquake (a) with a magnitude value of one integer greater than another earthquake (b) is ten times stronger as far as the Richter Scale and its descendants are concerned. Micro earthquakes are incredibly common and go unnoticed except by seismographs. Minor earthquakes are still common, may be felt particularly depending on the magnitude, but do not generally cause damage to buildings and other structures. Light earthquakes tend to be much more noticeable, though they generally do not cause notable damage. When an earthquake is designated as moderate, it is likely to be felt by all residents of an affected area, and it begins to be a threat to structures/buildings that are not well designed or are outdated in terms of architecture. Strong earthquakes begin to be dangerous and pose serious threats of structural damage, especially to epicentral areas; major and great earthquakes can be devastating with regards to the level of damage to an area. Great earthquakes typically only occur approximately once or twice per year, whereas major earthquakes are a bit more common.

While the Richter Scale is far from perfect, and seismology has developed significantly as far as measuring the strength of earthquakes, the Richter Scale is still used commonly – especially outside of the scientific community – to supply categorization of earthquakes. For the purposes of this paper, earthquakes will be referred to in terms of magnitude or category on a modified Richter Scale or a scale of similar categorical alignment, unless otherwise noted.[2]

[2] The United States Geological Survey (USGS) generally uses surface-wave or moment magnitude to identify the magnitudes of earthquakes. Much of the data which will be presented later in this paper will come from the USGS, or from sources using a similar formula/standard. Significant differences in data formulation will be noted as, and if, needed. An explanation of the formula(s) used by the USGS, as well as formulas/methods for other metrics related to measuring earthquakes can be found here: https://earthquake.usgs.gov/learn/topics/measure.php.

Contextualizing the El Reno Case

The earthquake that affected El Reno, Oklahoma in April 1952 had a magnitude of 5.5, which puts it firmly in the moderate category. Despite this, as previously mentioned, the damage associated with this event was reported as negligible. Whereas in a state such as California this sort of earthquake would be noteworthy for its low damage, but not unheard-of in terms of magnitude, this earthquake was historically strong for Oklahoma, and the city should be considered lucky to have avoided much damage.[3]

This case is important particularly in context with the history of seismic activity in the state of Oklahoma. The fact that this earthquake represents an outlier in Oklahoma history – especially prior to the current decade – can be used to inform one about the greater history of earthquakes and seismic activity in Oklahoma. This is to say, Oklahoma has not historically been the location of seismic activity of great frequency or magnitude.

To put this case into a more clear context, examine a brief history of significant earthquakes located in Oklahoma. The first time-period to be explained here will be the decade of the 1980s (1980-1989). According to the Oklahoma Geological Survey (OGS), seven earthquakes of at least magnitude 3 occurred with epicentral areas within the state during this period. These earthquakes were scattered in terms of both location and date. In May 1982, for example, a magnitude 3 earthquake was recorded in South Oklahoma (with an epicenter in or near Bryan County). This was both the Southern-most and Eastern-most located of these events, and no neighboring counties experienced significant earthquakes in the 1980s. The strongest

[3] In 2015, the National Oceanic and Atmospheric Administration (NOAA) began managing what is now known as the National Centers for Environmental Information (NCEI), an archive which includes quite a bit of data on worldwide earthquakes. The NCEI Significant Earthquake Database, in which information regarding death/injury counts and damage costs is kept for certain quakes, can be accessed online here: https://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1.

earthquake of the decade was a 3.7 in North-central Oklahoma (Kingfisher County) in December 1987. (Note that in the interest of clarity for the reader, when referencing the state of Oklahoma in regional/cardinal terms, the Western-most counties – Cimarron, Texas and Beaver Counties – will be excluded, as they have not been the location of an earthquake's epicenter in the last 28 years, at least.)

According to the OGS, fourteen significant earthquakes occurred in Oklahoma in the 1990s. These were also generally scattered in terms of location, but a couple of distinctions may be made here. Six of these earthquakes occurred in Northern Oklahoma, the other eight being located in Southern Oklahoma, with Central Oklahoma (latitudinally speaking in this case) being generally inactive during this period. Most of the stronger earthquakes occurred in the South, including the strongest of the decade – a 4.5 in September 1997 – which was located in Coal County. Garvin County in South-Central Oklahoma experienced four significant earthquakes in the 1990s, including a 4.1 in 1995, but each of these events occurred in different years.

In the following period, from the year 2000 to 2008, twelve significant earthquakes were recorded in the state of Oklahoma.[4] In 2000, 2001, and 2003, no significant earthquakes occurred. The earthquakes that did occur were mostly scattered throughout the South, and Northern Oklahoma was notably inactive during this period. No earthquake during these years had a magnitude of 4 or greater. The strongest of these earthquakes was recorded as a 3.8 and occurred in Comanche County in Southwest Oklahoma. More complete data on this 28-year period can be found in the following table:

[4] The data referenced in this section, summarized by the associated table, has been made available by the OGS and the USGS-NEIC. The government of Oklahoma has furthered the accessibility of this data and has mapped the data for convenient use/examination, retrievable at: http://earthquakes.ok.gov/what-we-know/earthquake-map/.

Significant (Min. 3.0 Magnitude) Earthquakes in Oklahoma, 1980-2008			
Time-Period	*Total Earthquakes*	*Average Magnitude*	*Highest Magnitude*
1980-1989	7	3.2	3.7
1990-1999	14	3.5	4.5
2000-2008	12	3.2	3.8

This is to illustrate that the reason the El Reno earthquake was Oklahoma's most powerful for decades afterward is because the state did not frequently experience earthquakes of significant magnitude in its history up to and including the year 2008. As will be discussed, however, this is no longer the case.

The Problem: Recent Seismicity in Oklahoma

The reason that this topic – Oklahoma's seismicity – is worth discussing is that historic trends of seismic activity do not reflect the state's situation in the past decade. In the past ten years, the number of significant earthquakes occurring in Oklahoma has spiked dramatically. While the Sooner State is not bereft of fault lines, they have not been particularly active in a very long time, and in a vacuum, they should not have awoken.[5] This is all worth researching for a number of reasons, but the most important is this: earthquakes are a security threat. Worldwide, earthquakes have accounted for nearly 800,000 estimated human deaths in the 21st century (through 2015).[6] Earthquakes of high magnitude can have serious negative economic impacts, especially in areas that are not well prepared to deal with them. While most of the casualties and

[5] This article published by *FiveThirtyEight* discusses the issue of recent seismicity spikes in Oklahoma and provides a useful map of the state's fault lines, credit for which goes to the OGS. Koerth-Baker, Maggie. (2016, September 9). (2016, September 9). How the Oil and Gas Industry Awakened Oklahoma's Sleeping Fault Lines. *FiveThirtyEight.com.* Retrieved from: https://fivethirtyeight.com/features/how-the-oil-and-gas-industry-awakened-oklahomas-sleeping-fault-lines/.
[6] USGS data retrieved from: https://earthquake.usgs.gov/earthquakes/browse/stats.php.

damage associated with earthquakes plague countries outside of the United States, many communities in the U.S. may not be prepared for a spike in seismicity such as is going on in Oklahoma. Moreover, if seismic activity in Oklahoma continues to increase, the state may quickly have a crisis on its hands.

It was mentioned earlier that from 1980 to 2008 Oklahoma experienced fewer than two significant earthquakes per year, none of which were greater than a light earthquake and only three of which exceeded magnitude 4.0. In 2009, however, the state was the site of twenty significant earthquakes – nearly double the total in the prior eight years – according to the USGS. The number increased over the next three years. In 2010, the total number of significant earthquakes recorded was 43. The following year, there were 63 significant quakes in the state, including one of magnitude 5.6 – a new record. 2012 might be considered a bit of a down year, with only 35 occurring, but 2013's total of 109 was greater than the previous two years combined.

In the three-year period following, Oklahoma was solidified as one of the most seismically active states in the country. In 2014 alone, the number of significant earthquakes in Oklahoma totaled 585 according to the USGS, and there occurred more light earthquakes in the state (15) than during the whole of the 1990s. Oklahoma was even more active in 2015; the only state in the country to have recorded more significant earthquakes than Oklahoma's nearly 900 in this year was Alaska. In 2016, another 639 significant earthquakes shook the state, and a new record-strongest quake (this one a magnitude 5.8) occurred.

This project will examine the available scholarship surrounding Oklahoma's spike in seismicity since 2009 as well as relevant research regarding the potential causes of earthquakes and the reasons that a problem such as this might be proliferated. Relevant scholarship regarding the extent to which seismicity in Oklahoma has spiked will be presented and discussed. The future of Oklahoma's earthquake problem will also be prognosticated, at least in as much as the research will allow.

In the context of certain forthcoming topics in this area, it is also important to examine the actions/policies of the state and federal government relating to this fairly new issue. Because of the fact that this phenomenon relates directly to the realm of homeland security, as well as to domestic economic and environmental stability, the manner in which state, local and federal government(s) deal with the issue – in Oklahoma and throughout the country – is of great importance. It is therefore worthwhile to examine the possibilities for public policy in this area, the approaches that have already been taken in dealing with this issue and those like it, and the prospects of issue networks relating to the issue.

Literature Review

Induced Earthquakes: The Science

An important area of study when it comes to the topic of spiking seismicity deals with the issue of the causes of earthquakes. In particular, questions as to whether or not an earthquake or earthquakes are natural or have causes related to human activity are relevant to this problem. Such questions can, at least at times, be difficult to answer, but there exists a plethora of research in this area.

In an article published in 2013 by *Science* magazine titled "Injection-Induced Earthquakes," Dr. William Ellsworth examined the causes of and dangers related to the increase in earthquakes in previously low-activity states such as Ohio, Texas, Arkansas and Oklahoma. In this piece, Ellsworth uses the term "induced earthquake" to refer to two kinds of earthquakes, those "triggered by anthropogenic causes that primarily release tectonic stress and those that primarily release stresses created by the industrial activity." The industrial activity referred to here is related to practices such as hydro-fracking and wastewater injection, two practices that have been the subject of great amounts of earthquake research. Ellsworth notes that increases in the occurrence microearthquakes have long been linked to hydrofracking, but historical trends do not account for the spike in significant earthquakes in the midwestern United States and other low-activity areas. Another important concept that Ellsworth tackles in this piece is the mechanics involved in earthquakes being caused. In layman's terms, a fault is constantly storing elastic energy, and this energy will only be released if it becomes too strong for the structure of the fault to store. Hence, the alteration of factors such as the strength of the rock on a fault or the stress it is under is instrumental in the induction of earthquakes. This is the reason that industrial activities – hydro-fracking and wastewater injection, for example – are linked to the occurrence of earthquakes. However, as the article states, determining the exact cause of an earthquake can be problematic. The changing of conditions on a fault might cause failure slowly or immediately, at locations of varying relation to activity, and the failure might be result of a number of events impacting the fault. Ellsworth uses cases in 2010-2011 in Oklahoma and Ohio to demonstrate the difficulty in pinpointing causation of earthquakes but claims that in the case of 5.0 and 5.7 moment-magnitude earthquakes in central Oklahoma there is clear reason to believe (based on depth and location of initialization of waves) that injection of wastewater was the underlying cause. In this case, the failure would have been building for nearly two decades resulting in record-setting activity in a historically quiet area.

In 2013, Dr. Austin Holland published an article in the *Bulletin of the Seismological Society of America* examining the relationship between hydro-fracking and the production of earthquakes. This case study analyzed data over a six-day period in January 2011 during which hydraulic fracturing was being conducted. Holland's study found a high correlation between the fracturing and the occurrence of earthquakes near the well. In this case 116 earthquakes, none exceeding a magnitude of 2.9, were recorded. All of these occurred during the hydro-fracking period, with no similar earthquakes being detected in periods before or after the hydraulic fracturing period. Perhaps the most significant and interesting piece of data to come out of this case study is that for two days fracturing was put on hold due to weather, during which time earthquakes also ceased. This study heavily supports what has been found in most cases when studying the effects of hydro-fracking on fault lines and seismicity – that hydraulic fracturing tends to produce high numbers of low-magnitude earthquakes.

A study published in July 2014 in *Science* magazine (the same publication for which Ellsworth's 2013 article was written), authored by Drs. Katie Keranen and Matthew Weingarten, *et al*., focused on the issue of wastewater injection and relating it to the spiking seismicity in Oklahoma and the central U.S. The authors found that the injection of water – be it wastewater, salt water, or water of another sort – into rock formations approximately 2-to-5 kilometers underground can be linked to the locations of hypocenters of many significant earthquakes in Oklahoma between 2008 and 2013. As well, the authors note that the volume of injection in central Oklahoma saw a dramatic increase between 2004 and 2008 due to the development and implementation of newer practices and technologies, such as high-rate disposal wells. Keranen and Weingarten, *et al*., state that conclusively proving the relationship between wastewater injection and significant seismicity spikes could be challenging, but their findings compellingly pointed to some of the highest-magnitude earthquakes in central Oklahoma from 2008 to 2013 being related to fluid migration from wastewater injection wells nearby. Further, as they put it, "twenty percent of the earthquakes in the central United States could be attributed to just four of the wells." This study is part of an important moment in the scholarship and science surrounding the larger issue as researchers began to move toward the conclusion that wastewater injection is linked to the occurrence of significant earthquakes, particularly earthquakes of dangerously high magnitudes.

An article written by Drs. Justin Rubinstein and Alireza Mahani for the journal *Seismological Research Letters*, titled "Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity," can – as the title suggests – serve to clear up misunderstandings and misinformation around the topic of recent induced earthquakes for the general populace. The authors first explain and refute six misconceptions they identify as common; some of the important points presented in this piece include the propositions that will follow. Rubinstein and Mahani make clear that hydrofracking is not the direct cause of most of the significant induced earthquakes in the U.S., most notably Oklahoma. Rather, the most impactful industrial activity in this area is wastewater injection. Wastewater disposal is also not solely the result of hydraulic fracturing practices; oil wells can produce saltwater, for instance, in significant volumes that must be disposed of even in the absence of hydrofracking. As well, they point out that injection can cause earthquakes far from their respective causal wells (up to twenty kilometers in some reported cases, according to the article and its sources), depending on fluid pathways associated with the deep injection and their proximity to certain faults. To add to this, not all injection wells can/do cause earthquakes. Some faults are not significant enough to produce significant earthquakes, different stresses can factor into fault failure in different ways, and some fluid migration will not impact the stresses of faults, whether nearby or not. Understanding this can help one grasp the challenge in proving the relationship between industrial activity and seismicity that at least plagued the research for some time prior to the writing of this article. Rubinstein and Mahani in this piece highlight the need for research regarding recent seismicity spikes in order to determine effective efforts for reducing the number of significant earthquakes as well as the risk of dangerous levels of seismicity in the future. They also make an important point about the variability in causes of induced earthquakes and illustrate that a wide approach to dealing with industrial activity is critical. Wastewater disposal is not an issue that is simply related to hydrofracking, and having a greater understanding/knowledge of faults, formations and fluid pathways will be necessary for implementation of safe industrial practices.

Building on the research referenced here, similar research and applying those ideas to data from the seismicity spikes since 2009, geologists, geophysicists and other experts in these fields have made important strides in the last few years as the science began to form into consensus regarding induced seismicity. In September 2017, Arthur McGarr and Andrew Barbour presented research on some of Oklahoma's most prolific earthquakes and seismic sequences occurring in 2016 under the title "Wastewater Disposal and the Earthquake Sequences During 2016 Near Fairview, Pawnee, and Cushing, Oklahoma" in *Geophysical Research Letters.* Their research strongly linked wastewater injection to hundreds of significant earthquakes and affirmed the connection between injection and the occurrence of four moderate earthquakes, some of the highest-magnitude quakes in the state's history. Another important concept that has not been detailed previously in this review is the idea of foreshocks, main shocks, aftershocks and sequences of significant earthquakes. When faults come to failure, they can release their energy/stress, so to speak, over varying periods of time and through any number of events. This is to say that the failure of a fault may cause any number of earthquakes. So, smaller earthquakes known as foreshocks will often occur on a fault for some time leading up to what will be the mainshock, or the strongest earthquake in a sequence (where most of the energy or stress is released). This is followed by another series of smaller earthquakes known as aftershocks. Depending on the level of pressure or stress, mainshocks and their corresponding foreshocks/aftershocks may be of any magnitude. Often times, and as observed in Oklahoma in the past decade, sequences can play out over the course of years. McGarr and Barbour examine, for example, a sequence in northwest Oklahoma that included 63 significant foreshocks, 89 aftershocks and climaxed with a moderate mainshock; this sequence took about two years to play out fully.[7] This is a very important facet of the issue of induced seismicity. Because faults can be activated by wastewater injection from varying levels of proximity and fault failure can be triggered slowly, the unpredictability of seismic sequences poses a prognostic challenge. A sequence might take years to come to a mainshock, and without proper data/understanding of subsurface pressure, a region might be underprepared for the timing and magnitude of that earthquake. Furthermore, without proper monitoring of pressure and industrial activity, it could be difficult to predict mainshocks in line with distinguishing foreshocks and aftershocks. That is, if the phases of various sequences are not well-monitored, there may be predictive difficulties associated with those sequences.

With a great amount of research on induced earthquakes, seismicity in Oklahoma and throughout the country in the past decade and the different impacts of industrial activities, the science has arrived at what is essentially consensus, or as close to consensus as can be

[7] McGarr and Barbour cite prior research written for *Geophysical Research Letters* by William Yeck, et al. Both articles attribute these sequences to wastewater disposal, though they test different hypotheses. Yeck, W. L., Weingarten, M., Benz, H. M., McNamara, D. E., Bergman, E. A., Herrmann, R. B., ... & Earle, P. S. (2016, September 27). Far-Field Pressurization Likely Caused One of the Largest Injection Induced Earthquakes by Reactivating a Large Preexisting Basement Fault Structure. *Geophysical Research Letters*, *43*(19).

reasonably expected. This consensus – the clear relationship between wastewater disposal and the spikes in seismicity – is discussed by experts Thea Hincks, Willy Aspinall, Roger Cooke and Thomas Gernon in their March 2018 *Science* magazine report “Oklahoma's Induced Seismicity Strongly Linked to Wastewater Injection Depth.” The article explains some of the complexities of the relationship such as fluid migration and the importance of depth in impacting pressure. It also emphasizes the importance of ongoing research in determining how governments should regulate industrial activity and monitor hazards moving forward. What the article represents, however, is an important assessment of the progress made in the scientific research regarding induced earthquakes and industrial activity, and how the issue has moved from primarily determining the causal factors in inducing the U.S. seismicity spikes to determining how to manage and mitigate the hazards associated with these induced earthquakes.

Problem-Solving Through Policy

With the science around this issue well-established, the problem moves further into the realm of developing and implementing policy with the aim of reducing seismic hazards throughout the country. While great progress has been made in recent years in terms of the science, translating this to policy implementation can be difficult, and may take some time.

In 2017, Fenner Stewart and Allan Ingelson examined the U.S. political climate regarding this issue, and more specifically the manner in which it can and has impacted regulatory progress in recent years. Their article, titled “Regulating Energy Innovation: US Responses to Hydraulic Fracturing, Wastewater Injection and Induced Seismicity,” was published in the *Journal of Energy & Natural Resources Law* in May that year. The authors claim that while researchers had clearly established a causal relationship between wastewater injection and induced seismicity, this is sometimes not enough to prompt important policy changes on an issue, particularly when it comes to issues of political controversy (whether such controversy is earned or not). One reason that Stewart and Ingelson identify as potentially explaining the political reluctance to rely on the science relates to misconceptions about what the science has found and the way the issue is presented for public review. Those who tend oppose regulation of industrial activity to reduce seismic hazards commonly present the issue as primarily pertaining to hydraulic fracturing. This allows the misleading presentation of findings that hydraulic fracturing is not the cause of significant earthquakes; while true, this deflects from the more important issue of wastewater disposal, the findings relating to which are both more concrete and more pressing. An outsider to this issue might be unfamiliar with the science and may be presented with the issue as dealing only or primarily with hydraulic fracturing, in which case they would likely also be told – not incorrectly, note – that the science does not indicate that these earthquakes are induced by fracking. Refer to the misconceptions laid out by Rubinstein and Mahani (2015); the problem of induced earthquakes is poorly communicated to the layman. Stewart & Ingelson posit that problems like this have allowed varying levels of regulatory stagnation in states such as Texas, Colorado, Oklahoma, Ohio and New Mexico. The authors point to policy in California promoting the sharing of information between government agencies and hydraulic fracturing operators in order to avoid hazardous activity and monitor potential risks as a potentially critical value moving forward.[8]

Political scientists Charles Davis and Jonathan Fisk authored a study published in *Society & Natural Resources* in February 2017 examining the assessments that legislators and regulators can make when dealing with the issue of induced seismicity. The study focuses on three factors: "the emergence of quakes as focusing events, the economic importance of oil and gas to state

[8] See California Public Resources Code 3106.

jobs and revenue, and selected characteristics of earthquakes as a policy issue, *i.e.*, complexity and categorical precedence" (p. 1009). The case study used Colorado, Oklahoma, Arkansas, Kansas, Texas and Ohio and found that generally the increasing relevance of earthquakes as focusing events was most frequently (relative to the other variables) a factor in policy decision-making. In each of these cases, hazard mitigation and injection regulation moved slowly and was implemented incrementally – especially in those states that were found to be more dependent on the oil and gas industries within their economies. The authors noted that there was too little available data in this area for widely applicable conclusions to be drawn, and that further research should be done as induced seismicity becomes a more acted-upon issue in the U.S. Perhaps the most important thought that is presented in this article, pertaining to the findings, is that non-legislative actions to mitigate risk in seismically active states and areas have been and will continue to be an important means of dealing with this issue (at least in the short-term), and that such actions should be the focus of some future research.

Research

The case study here will focus on the actions taken by the Oklahoma state government – through the Oklahoma Corporation Commission (OCC) Oil and Gas Conservation Division (OGCD) and in cooperation with the OGS – between 2015 and the present. Rather than examining the effectiveness of the approaches taken by the OCC in mitigating the hazards associated with seismicity in Oklahoma, the primary interest of this study will be to explore how the OCC has been tackling the issue and the positions being held by the commission as far as defining the issue. This is because at present the more pertinent issue regarding induced seismicity in Oklahoma and throughout the U.S. is the implementation of policy with the aim of regulating industrial activities such as hydraulic fracturing and wastewater disposal. The effectiveness of these policies will be better determined by seismological examinations of areas affected by induced seismicity and by seismicity mitigation policy, and the effects of government actions in Oklahoma may be difficult to determine accurately until some time after policy implementation. This does not mean that it is not worth examining/discussing seismicity data in Oklahoma in context with the OCC's actions during relevant timeframes, but that it will be limited in terms of the conclusions that one might reasonably and responsibly draw. It should be noted as well that such studies in other states faced with the problem of induced seismicity spikes – Texas, Pennsylvania, Colorado, etc. – would be worthwhile, but that this case study is most interested in a focused examination of the government approach to this problem in Oklahoma as it is the most affected by induced seismicity as of this project's being written. This is an important policy issue throughout much of the country.

The information to be presented in this section deals with directives put forth by the OCC between March 2015 and April 2018 and will be based on press releases by the OCC in and regarding that time frame. The expectation based on the science around induced seismicity in Oklahoma and the U.S. is that regulation of injection wells will have been the focus of the OCC's mitigation efforts but that developments of these efforts will have been incremental and their approach to regulating hydraulic fracturing will have been considerably lesser. The information will date only as early as 2015 because the OCC, while providing a brief history of earlier actions as a base, presents 2015 as an important marker in its Earthquake Response Summary (from which much of the information presented in this section will be gleaned).[9]

[9] The Earthquake Response Summary is a living document which consists primarily of explanations of and links to actions taken by the OCC in its ongoing efforts to deal with induced seismicity in Oklahoma. Relevant links to documents referenced in the Summary will be provided in further footnotes as available. The document is made available on the commission's website and can be retrieved here, having last been update April 9, 2018: http://www.occeweb.com/News/2018/04-09-18EARTHQUAKEACTIONSUMMARY.pdf.

Notable OCC/OGCD Actions

The first major action taken by the OCC in this period took place on March 25, 2015.[10] Two important terms involved in the OCC's seismicity mitigation efforts are "area of interest" (AOI) and the "traffic light system." The term AOI referred originally to 10 km (diameter) areas surrounding 4.0 magnitude quakes and was expanded on March 25 to include "swarms" of earthquakes (defined as at least two quakes with epicenters within a quarter-mile of each other, one of which having a magnitude of at least 3). The traffic light system refers to an evolving system of regulatory guidelines designed to mitigate induced seismicity. Some highlights of this system include as of March 25: the requirement for special permits to be obtained for the operating of injection wells within three miles of a stressed fault or six miles of an earthquake swarm or magnitude 4+ quake; reviews of disposal operations within an AOI, and; daily recording/measuring of well pressure and disposal volume into the Arbuckle formation, which sits just above basement rock in Oklahoma. The OCC in this directive required the operations at 347 injection wells to provide proof within the next month that injection was not taking place below the Arbuckle formation. The directive required operators without plans to plug back – or reduce the depth of their wells – to reduce their injection volume by 50%.

In June of the same year, the OCC built on the tenets of the March directive.[11] The OGCD again expanded the coverage of AOIs, this time applying their regulations to 211 more disposal wells and again gave operators one month to prove that they were not injecting into the Arbuckle. As well, the directive updated OCC rules to require operators to plug back all wells

[10] Related document retrieved from: http://www.occeweb.com/News/2015/03-25-15%20Media%20Advisory%20-%20TL%20and%20related%20documents.pdf.
[11] Related document retrieved from: http://www.occeweb.com/News/DIRECTIVE-2.pdf.

injecting into the Arbuckle, rather than allowing them to cut the volume of injection while continuing to operate.

From then until February 2016 the OGCD dealt with problematic injection wells in less-sweeping manners. For the most part during this period the division acted in response to seismic events within the AOIs already established and administering the ceasing of operations at wells nearby significant earthquakes. In most of these cases, however, well operators were only required to cut disposal volume, typically by about 25-50%. In early December, for instance, the OCC required four wells to be shut in and 47 other wells to cut volume, in response to a light earthquake near Byron, OK. According to the OGCD, the net disposal reduction in this area would be about 47% volume.[12]

Between February and April 2016, the OGCD implemented regional response plans for western Oklahoma (developed in February)[13] and central Oklahoma (developed in March).[14] These were by far the most substantial actions taken by the OCC in dealing with induced seismicity since June 2015. Both regional plans expanded the AOI, increasing coverage by about 10,000 square miles. However, while the regional response plans allowed the OGCD greater reach with regards to injection wells in the state, they did not update the existing regulatory options available to the OCC. That is, they expanded the jurisdiction of previously established OCC rules, but did not implement more aggressive regulatory options for the handling of wells not in line with OGCD standards.

[12] Related document retrieved from: http://www.occeweb.com/News/12-03-15BYRON-CHEROKEE_MEDFORD%20EARTHQUAKE%20RESPONSE.pdf.
[13] Related document retrieved from: http://www.occeweb.com/News/2016/02-16-16WesternRegionalPlan.pdf.
[14] Related document retrieved from: http://www.occeweb.com/News/2016/03-07-16ADVISORY-AOI%2C%20VOLUME%20REDUCTION.pdf.

Throughout much of the remainder of 2016, the OGCD primarily regulated operations within the AOI and responded to new areas affected by significant seismic events (such as the 5.8 quake in the Pawnee area).[15] Later in the year the OCC also began cooperating more often with the Environmental Protection Agency (EPA) in their mitigation efforts. The final significant OCC action in 2016 came in mid-December. OGCD director Tim Baker cited research by Dr. Austin Holland as reason to proactively apply regulations to hydraulic fracturing operations in the South-Central Oklahoma Oil Province (SCOOP) and Sooner Trend Anadarko Basin Canadian and Kingfisher counties (STACK) areas. These areas were expected by the OCC to account for a great amount of the state's industrial activity in the near future, and the commission assessed that the area would produce relatively little wastewater. Earthquakes of magnitude 2.5 or greater would, according to this directive, require that fracturing operations be closely monitored or suspended. This action was the first notable regulatory action taken by the OCC with regards specifically to hydraulic fracturing.[16]

In February 2017, the OGCD issued a directive capping the injection rates of wastewater disposal for future operations.[17] While the directive would not reduce disposal volumes at the time, it limited operators' ability to increase injection rates going forward. The cap applied to approximately 654 injection wells operating within the AOI as well as certain wells not previously volume-restricted. This was the only widely-applied regulatory directive issued by the OCC in 2017 regarding induced seismicity. For the most part the commission was fairly inactive in dealing with the problem compared to previous years, except for in assessing hazard maps and progress of prior regulatory actions. The most notable action taken to date in 2018 was

[15] Related document retrieved from: http://www.occeweb.com/News/2016/09-12-16Pawnee%20Advisory.pdf.
[16] Related document retrieved from: http://www.occeweb.com/News/2016/12-20-16SCOOP-STACK.pdf.
[17] Related document retrieved from: http://www.occeweb.com/News/2017/02-24-17%20FUTURE%20DISPOSAL.pdf.

a directive that built on the December 2016 hydraulic fracturing plans for the SCOOP and STACK plays, furthering mitigation efforts related to hydro-fracking.[18] The directive lowered the minimum magnitude of action-demanding earthquakes and required all operators within these areas to have access to seismic arrays in order to monitor induced seismicity actively.

Conclusions

In assessing the OCC's approach to induced seismicity in Oklahoma it may be important to consider the following. First, the total coverage of the AOI throughout the state is about 15,000 sq. miles currently and has not increased substantially since 2016, and volume reduction has been applied to about 11,000 sq. miles of that area. Second, the most significant directives issued by the commission have tended to come following some in-flow of funding to the OCC/OGCD (whether in the form of grants by the Oklahoma Secretary of Energy and Environment, emergency funding by the Governor, or other one-time allotments of funding). Third, the actual effectiveness of the approach will not be easily measured perhaps for years to come.

The non-legislative approach to induced seismicity in Oklahoma has, as expected, been slow and incremental. It was not until 2015 that the OCC took significant actions in implementing widely-applied regulations to industrial activity in effort to mitigate earthquakes/seismic hazards. As well, it was not until late-2016 that regulators began to focus any effort on dealing with hydraulic fracturing specifically. Moreover, many of the actions taken by the OCC have built on prior steps. Directives have often served to expand the applications of previous rules or regulations, effectively increasing the reach of prior efforts such as applying the

[18] Related document retrieved from: http://www.occeweb.com/News/2018/02-27-18PROTOCOL.pdf.

traffic light system to more wells, increasing total AOI coverage, or updating/tightening past restrictions.

One of the biggest positives that can be attributed to the OCC's response to induced seismicity is the emphasis on information recording/sharing. One of the core regulatory focuses of the OGCD's directives has been the monitoring of injection volumes, operation durations, seismographic readings, injection depth, etc., and the reporting of that information to the commission frequently. Such information networking will be important to solving the problem going forward (as was noted by Stewart and Ingelson, 2017) throughout the country, and has been important in tackling similar environmental/security issues nation-wide. In addition, the OCC is seemingly learning from the data that has become available to it, as evidenced by such adaptations as enforcing plugging back/shutting in of wells at certain high-risk depths.

It is important to note, though, that the slowing of improvement/adaptation with regards to regulatory approaches may be a serious negative. If it is to be assumed that Oklahoma's problem with induced seismicity – even if only as associated with wastewater injection – has not been solved, then the expectation should be that the OCC would continue to tune its requirements and rules, continuing to reduce injection volumes and well depths. While it is good that the commission has begun to tackle induced seismicity associated with hydraulic fracturing, these efforts should ideally not take away from the progress being made in the area of wastewater disposal. The OCC has often noted that significant earthquakes per day have been declining in each of the past three years, but these numbers – approximately 1.7 per day in 2017[19] – are still hundreds of times the rates prior to 2009, and much higher than between 2009

[19] OGS data retrieved from: http://www.occeweb.com/News/2018/03-29-18Statement-SeismicMap.pdf.

and 2012. It is also difficult to determine whether the decrease in significant earthquakes throughout the state can be attributed to the OCC's efforts, a temporary dip in induced seismicity or some other explanation.

Further research on this topic will be important, and the on-going OCC efforts will be worth keeping an eye on. Based on the slow progress of action by the OCC and the tendency of the commission to act more widely with influxes of funding, it is not unlikely that the OGCD is in need of greater funding in order to solve the induced seismicity problem. Investigation of the politics surrounding the funding of the OCC's seismicity response would therefore be worthwhile. It will also be worthwhile to examine the efforts in other states – such as Ohio, Colorado and Texas – to mitigate induced seismic hazards, and to compare those efforts to the ones made in Oklahoma at the state level. Because induced seismicity is a problem in many parts of the country, the networking of information regarding policy options and seismicity research will be helpful to returning Oklahoma to natural, safe levels of seismicity, and to preventing hazardous seismicity spikes throughout the country.

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