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Oklahoma earthquakes and the price of oil☆

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ABSTRACT

The process of hydraulic fracturing has unlocked an unprecedented amount of oil and gas in the United States. Hydrocarbons are not the only output from this process, though, as billions of barrels of "produced" water are extracted and subsequently pumped back underground. This process of injecting produced water into disposal wells has been causally linked to the rise in earthquakes. Here I show how the amount of earthquakes in Oklahoma are positively linked to the price of oil, and further find that the decrease in earthquake activity in Oklahoma is due to both the drop in oil prices and the regulatory directives of regional authorities. The estimated impact of the various shut-in policies have been small compared to the reduction in earthquakes due to the broad price decline, though. I find that the drop in oil prices that began in mid-2014 led to as large of a reduction in earthquakes as the combined effect f new policies that started in March of 2015.

1. Introduction

The surge in oil and gas supply due to hydraulic fracturing or 'fracking' has transformed markets and industries with wide ranging effects impacting coal burning facilities' retirement dates and the follow-through on nuclear power plant additions. Interestingly enough, though, oil and gas are not the primary outputs of this type of production – water is. At the nascent stages of modern unconventional extraction, circa 2007, onshore oil and gas wells contributed as much as 17.82 billion barrels of 'produced water' (Clark and Veil, 2009). This water is later separated from the oil and gas and re-injected into disposal wells that are often at greater depth than the water originated.[1] Alongside the surge in U.S. oil and gas supply, and the disposal of produced water, there has been a staggering increase in the amount of earthquakes felt in areas where waste-water injection is taking place (Ellsworth et al., 2015). Although wastewater-induced earthquakes have been felt in other areas,[2] the state of Oklahoma has witnessed a striking increase in earthquake activity. Figure one shows just how unprecedented the change in earthquake activity has been. In the top panel all earthquakes from January 1 2000 through the end of 2009 are plotted; in the bottom panel the amount of earthquakes witnessed through 2016 are shown. Clearly, there has been a distinct increase over these seven years. In this paper I discuss the economic drivers of induced seismicity and further explore how effective regional authorities have been in reducing the amount of included earthquakes.

Seismicity in Oklahoma serves as a very unique case because the current earthquake rate is 300 times higher than the historical rate (Weingarten, 2015). In fact, the seismicity rate in Oklahoma has increased so drastically that it is now more common to have a magnitude 3.0 or larger earthquake in a single day than in entire years prior to 2008. Specifically, Weingarten (2015) shows that the rate of magnitude 3.0+ earthquakes was $1\frac{1}{2}$ *per year* prior to 2008, and $2\frac{1}{2}$ magnitude 3.0 + earthquakes *per day* after 2008. Linking now to the amount of produced water, the advent of hydraulic fracturing has significantly increased the amount of disposal because the targeted formations often have a large amount of 'associated' water that is high in salinity and is brought to the surface as a bi-product. For example, Nicot et al. (2014) find that there was a five fold increase in produced water disposal in the Barnett shale between 2000 and 2011 – from 8.8 thousand acre feet per year to 45.7 thousand acre feet per year. In Oklahoma, approximately 849 million barrels[3] of produced water per month were injected into disposal wells at the beginning of the fracking boom. By 2014 this amount had grown to 1.54 billion barrels per month. For comparison, produced water in the state of Texas increased from 33.8 million barrels

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[1] Hydraulic fracturing is a water-intensive practice, however wastewater from the production process is a small percentage of the total amount of water that is ultimately injected into disposal wells.

[2] As shown in Hornbach et al. (2015) and Llenos and Michael (2013).

[3] A barrel is 42 U.S. gallons.

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per month in 2007–81.1 million barrels per month in 2014 (Kuchment and Kuchment ()). For context, this means that nearly 19 times more produced water was injected within Oklahoma than Texas; even though Texas has more than three times the land area.

In this article, I use the sudden and dramatic increase in seismic activity witnessed in Oklahoma and determine how this rise in earthquakes is related to the economic viability of oil production while controlling for aftershock effects and policy efforts. I do this by considering time-series data on daily earthquake counts from January 2009 to July 2016. This date range includes a time period before earthquakes were common in Oklahoma, and this sample period includes a large amount of price variation - the wholesale price of oil, the West Texas Intermediate (WTI) price, ranged from \$26 to \$145 per barrel. I am also able to use state policy interventions to identify the effect of price changes on earthquake activity and, further, determine whether or not these policy interventions are responsible for the recent decline in earthquake activity. While earthquake activity drastically increased after 2009, local policymakers were slow to act and the first directive intended to reduce wastewater disposal occurred in March of 2015. Thus, there is a clear pre-policy era in which no policy or disposal directive had been passed, and a clear post-policy era in which multiple well shut-ins and disposal limits were set. Across many model specifications I find that a 10% decrease in the wholesale price of oil leads to a more than 3.4% decrease in earthquakes per day. Further, I find that there has been a statistically discernible decrease in daily earthquakes in the era of policy measures. Specifically, I find that the policy-era is associated with 2.7 fewer earthquakes per day Fig. 1.

1.1. Background

Induced seismicity is by no means new. Beginning as early as 1894 there are accounts of induced seismicity in Johannesburg due to gold mining operations (McGarr, 2002). There are also historical accounts of people close to the oil and gas industry applying for earthquake insurance curiously prior to earthquakes occurring (Hough and Page, 2016). Since then, rigorous methods have been applied to linking fluid injection and the rise in earthquakes, and there is broad scientific consensus that swarms of induced earthquakes are due to injection activities as measured by pumping volumes and rates (McGarr et al., 2015; Ellsworth, 2013; Weingarten et al., 2015; among others). Specific to the earthquakes in Oklahoma, Keranen et al. (2013) show that the surge in earthquake activity is due to wastewater injection. Llenos and Michael (2013) and McNamara et al. (2015) provide even further evidence linking injection wells to induced seismicity in Oklahoma. The distinction between naturally occurring and induced earthquakes is also well researched. Studies have shown that the maximum magnitude of induced earthquakes may be smaller than what is seen with natural earthquakes, but they also suggest that induced earthquakes can trigger larger earthquakes on known or unknown faults (McGarr, 2014; Petersen et al., 2016). Additionally, induced earthquakes tend to occur in swarms (many happening in the same area in quick succession) and they tend to happen at shallower depths than natural earthquakes (Gomberg and Wolf, 1999; van der Elst et al., 2016). While the causal link between wastewater disposal and earthquakes is established, the exact mechanism and dynamics are still under debate. For example, we do not know with certainty how much time it takes for disposal to trigger an earthquake, nor do we know with certainty the distance between where wastewater disposal occurs and where a triggered event could occur. New research by Peterie et al. (2018) shows that earthquakes could be triggered up to 90 kilometers away - more than 10 times further than prior research suggested. Terry-Cobo (2018) shows that researchers in the geology field have called this result into question, though. While there has clearly been a flurry of research associated with induced seismicity given the recent phenomena of earthquakes in traditionally non-seismic areas, the fact that injection can cause earthquakes has actually been established within the scientific literature for nearly 50 years. Healy et al. (1968) showed how high pressure injection caused earthquakes to occur in the Denver area. Following the Denver earthquakes, scientists were later able to control the amount of earthquakes by changing fluid pressure at four wells in Rangely, Colorado (Raleigh et al., 1976).

Policymakers and regulating authorities were slow to act in regulating disposal well volumes in Oklahoma, but following a litany of published scientific literature, and complaints from constituents, the state authority in charge of regulating oil and gas operations did begin to issue directives and limit disposal volumes in areas that witnessed large or frequent earthquakes in 2015. Armed with information, the Oklahoma Corporation Commission (OCC) issued several policy directives aimed at combating the dramatic increase in earthquake activity between 2015 and 2016 with the first, and most wide-ranging of these directives, issued on March 25th of 2015. In the March 25th directive, the Corporation Commission defined what they refer to as an “area of interest” which largely coincided with the Arbuckle formation and determined an action plan for disposal wells within this area. The Arbuckle formation is the basement layer formation that operators injected produced water into, and published research indicates that fluid pressure differences at this great of a depth are what cause induced earthquakes. Following the March 25th directive the next substantial directive was issued on July 17th, 2015. Between the two of these directives a total of 558 disposal wells were told to check the depth that they were disposing water and either: reduce daily volume disposed, ‘plug back’ and reduce the depth that they were disposing, a combination of these two actions, or to cease operations entirely.[4] Following the first two major directives the OCC has mostly issued smaller, targeted directives in response to large scale events or earthquake swarms and they have coordinated actions with disposal well operators in close proximity to the swarm or large tremblor. Since the original, large-scale directives more than 15 other individual directives have been issues forming a patchwork of policy prescriptions throughout the state of Oklahoma. A complete list of directives dates and actions is shown in Box 1.

Since the era of wastewater regulation began the amount of daily earthquakes has declined. Fig. 2 shows the change in earthquake activity over time with the four week moving average of daily earthquake counts (top panel). Following the first directive for plugging back and reducing disposal volumes by the OCC, shown with the vertical bar on March 25th, earthquake activity seemed to wane. At first glance, the top panel of Fig. 2 seems to show that the policy-era of shut-in policies have been successful in reducing the amount of earthquakes - the four-week moving average broadly declines after this date. However, the effect of the Corporation Commission's policies must be taken in context with the broader oil market. Although these policies are clear in their direction and definition of risk-prone areas, they have an unfortunate lack of generality in reducing disposal at wells outside of specified areas or target wells. The list of all OCC directives shows just this, that actions and directives have been issued following major events or earthquake swarms in order to limit disposal volumes in affected areas or at specific disposal wells. Thus, the directives issued by the OCC are, by nature, purely reactive and form a patchwork of policies regulating disposal-induced seismicity. It is not surprising, then, that market dynamics and wholesale price changes can more immediately impact drilling activities and the quantity supplied of oil and gas (and hence produced water and disposal) than these policies. The bottom panel of Fig. 2 shows the wholesale price of oil with the same vertical line for March 25th indicated. All else equal, when oil prices fall the amount of oil production also declines as it becomes less economically viable to produce. Thus, while the policy-era of new disposal directives seems to have reduced the amount of daily earthquakes, it is just as likely that there is simply

[4] A list of all directives, press releases, etc. is available from Oklahoma Corporation Commission ().