Earthquakes Induced by Hydraulic Fracturing Are Pervasive in Oklahoma

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First published: 28 November 2018

2. Wastewater disposal is generally accepted to be the primary cause of the increased seismicity rate in Oklahoma within the past decade, but no statewide analysis has investigated the contribution of hydraulic fracturing (HF) to the observed seismicity or the seismic hazard. Utilizing an enhanced seismicity catalog generated with multistation template matching from 2010 to 2016 and all available hydraulic fracturing information, we identified 274 HF wells that are spatiotemporally correlated with bursts of seismicity. The majority of HF-induced seismicity cases occurred in the SCOOP/STACK plays, but we also identified prominent cases in the Arkoma Basin and some more complex potential cases along the edge of the Anadarko Platform. For HF treatments where we have access to injection parameters, modeling suggests that poroelastic stresses are likely responsible for seismicity, but we cannot rule out direct pore pressure effects as a contributing factor. In all of the 16 regions we identified, ≥75% of the seismicity correlated with reported HF wells. In some regions, >95% of seismicity correlated with HF wells and >50% of the HF wells correlated with seismicity. Overall, we found ~700 HF-induced earthquakes with $M \geq 2.0$, including 12 events with M 3.0–3.5. These findings suggest state regulations implemented in 2018 that require operators in the SCOOP/STACK plays to take action if a $M > 2$ earthquake could have a significant impact on future operations.

Introduction

3. The seismicity rate in the central and eastern United States has increased fortyfold within the past decade, predominantly as a result of human activities (Ellsworth, **2013**; van der Baan & Calixto, **2017**). The increase in seismicity rate within the United States has largely been attributed to large-volume disposal wells injecting wastewater into deep sedimentary formations (e.g., Keranen et al., **2014**; Rubinstein & Mahani, **2015**). Oklahoma, the state with the most prominent seismicity rate increases, had more cataloged $M > 3$ earthquakes than California within the past 5 years. The recent seismicity in Oklahoma is largely the result of increased volumes of wastewater that is coproduced from oil extraction (e.g., Walsh & Zoback, **2015**). The two largest-magnitude cases of injection-induced seismicity in the world within the past decade both occurred in Oklahoma: the 2016 M 5.8 Pawnee earthquake (Walter et al., **2017**; Yeck et al., **2017**) and the 2011 M 5.7 Prague earthquake (Keranen et al., **2013**). Both sequences were attributed to wastewater disposal (WD) wells.

4. While WD is the primary cause of induced earthquakes in the United States within the past decade, other human activities such as carbon sequestration (e.g., Kaven et al., **2015**),

geothermal energy (e.g., Johnson, **2014**), and hydraulic fracturing (HF; e.g., Skoumal et al., **2015c**) have also been attributed to seismicity. While microseismicity ($M < 1$) is an inherent component of the HF process (Warpinski et al., **2012**; Wolhart et al., **2006**), stimulations that induce larger-magnitude events along preexisting faults (*HF-induced seismicity*) are less common. HF-induced seismicity can also be differentiated from the inherent microseismicity by the locations of the events; the inherent microseismicity associated with fracture creation/opening are typically isolated near the formation being stimulated, while induced seismicity has been observed in the Precambrian basement or other sedimentary layers (e.g., Kozłowska et al., **2018**). Individual case examples of HF-induced seismicity have been now be identified in Alberta (e.g., Wang et al., **2016**), Arkansas (Yoon et al., **2017**), British Columbia (e.g., B.C. Oil and Gas Commission, **2012**), California (Kanamori & Hauksson, **1992**), China (e.g., Lei et al., **2017**), England (Clarke et al., **2014**), Ohio (e.g., Skoumal et al., **2015a**), Oklahoma (e.g., Holland, **2013**), Pennsylvania (Skoumal et al., **2018**), and West Virginia (Skoumal et al., **2018**).

5. Several previous studies have argued that HF has a much lower risk of inducing felt ($M \geq 3$) seismicity than WD considering the shorter duration of injection (days to weeks versus months to years, respectively) and the smaller total volume of injection (NRC, 2013; Ellsworth, **2013**; Rubinstein & Mahani, **2015**). This interpretation was based on the few documented cases of HF-induced seismicity, with the cases consistent of small-magnitude events. Since these interpretations were made, larger-magnitude earthquakes that have been attributed to hydraulic fracturing have occurred, including the 2015 M 4.6 earthquake in British Columbia, Canada (Atkinson et al., **2016**; Mahani et al., **2017**), and the 2016 M 4.7 earthquake in the Sichuan Basin, China (Lei et al., **2017**). Additionally, while the number of cases identified prior to these studies was limited (Clarke et al., **2014**; Darold et al., **2014**; Friberg et al., **2014**; Holland, **2013**), more recent studies have found a higher prevalence of HF-induced seismicity than would have been previously expected (Atkinson et al., **2016**; Skoumal et al., **2015a**).

6. Considering these findings, this study seeks to examine the prevalence of HF-induced seismicity in Oklahoma. There were only two previously reported cases of HF-induced seismicity in Oklahoma (Darold et al., **2014**; Holland, **2013**). These two documented examples occurred in southern Oklahoma and had seismicity with $M \leq 3.2$. Both HF and WD wells in Oklahoma are ubiquitous throughout many parts of the state (Figure **1**). As a result of the continued practice of hydraulically stimulating wells in Oklahoma, it is important to understand the likelihood of HF-induced seismicity and identify any potential hazards posed by these operations.