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Key Points:
- Cushing earthquakes have transferred stress to faults capable of producing larger earthquakes
- Increased earthquake hazard exists for energy industry infrastructure near Cushing Oklahoma
- The Cushing sequence is likely related to wastewater injection

Supporting Information:
- Figures S1–S5, and Tables S1–S3

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Reactivated faulting near Cushing, Oklahoma: Increased potential for a triggered earthquake in an area of United States strategic infrastructure

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Abstract In October 2014 two moderate-sized earthquakes (*Mw* 4.0 and 4.3) struck south of Cushing, Oklahoma, below the largest crude oil storage facility in the world. Combined analysis of the spatial distribution of earthquakes and regional moment tensor focal mechanisms indicate reactivation of a subsurface unnamed and unmapped left-lateral strike-slip fault. Coulomb failure stress change calculations using the relocated seismicity and slip distribution determined from regional moment tensors, allow for the possibility that the Wilzetta-Whitetail fault zone south of Cushing, Oklahoma, could produce a large, damaging earthquake comparable to the 2011 Prague event. Resultant very strong shaking levels (MMI VII) in the epicentral region present the possibility of this potential earthquake causing moderate to heavy damage to national strategic infrastructure and local communities.

1. Introduction

Cushing, Oklahoma, is an area of concern because it is a major hub of the U.S. oil and gas pipeline transportation system that includes operational sections of the Keystone pipeline [https://www.npms.phmsa.dot.gov]. The earthquake sequence in October 2014 (*Mw* 4.0 and 4.3) reactivated a complex intersection of conjugate strike-slip structures within the Wilzetta-Whitetail fault zone, similar to the 2011 Prague, Oklahoma (*Mw* 5.6) earthquake sequence. To place constraints on the potential hazard of future earthquakes in the region, we examined the source characteristics of the October 2014 Cushing earthquake sequence and resultant Coulomb failure stress change (ΔCFS).

The strong shaking (MMI VI) (Okalahoma Geological Survey, 2011, http://www.okgeosurvey1.gov/pages/earthquakes/information.php) felt during the October 2014 Cushing earthquake sequence led the Oklahoma Corporation Commission (OCC) to temporarily close down several wastewater injection wells in the epicentral region. Minor damage was also reported throughout the city of Cushing including cracked plaster, broken window glass, and items thrown from shelves. The *Mw* 4.3 earthquake was widely felt up to 210 km north in Wichita, Kansas, and 240 km east in Fayettville, Arkansas. In November 2011, the same fault zone hosted a sequence of moderate-to-large, damaging earthquakes, near the town of Prague, which included the largest recorded earthquake in Oklahoma history (*Mw* 4.8, 5.6, and 4.8) [*McNamara et al.*, 2015; *Keranen et al.*, 2013]. Based on previous studies linking hydraulic fracturing [*Holland*, 2013a] and wastewater disposal [*Keranen et al.*, 2014; *Weingarten et al.*, 2015; *Walsh and Zoback*, 2015], to increased seismicity in central Oklahoma, a study of the changing earthquake hazard caused by the October 2014 Cushing sequence and its relationship to wastewater injection is important in order to understand potential damage to critical infrastructure in the region.

2. Identifying Reactivated Faults Near Cushing Oklahoma

Fault length, orientation, and associated seismicity are key inputs to seismic hazard assessment. With this in mind, we examined the source characteristics of the October 2014 Cushing earthquake sequence. Using continuous data from portable seismic stations deployed in the vicinity of the epicenter (Figure 1) and template waveforms from the *M* 4.3 earthquake, we ran a subspace detection algorithm to identify subsequent aftershocks (after *Benz et al.*, 2015) (Figure 2). Eighty well-recorded earthquakes were located using the

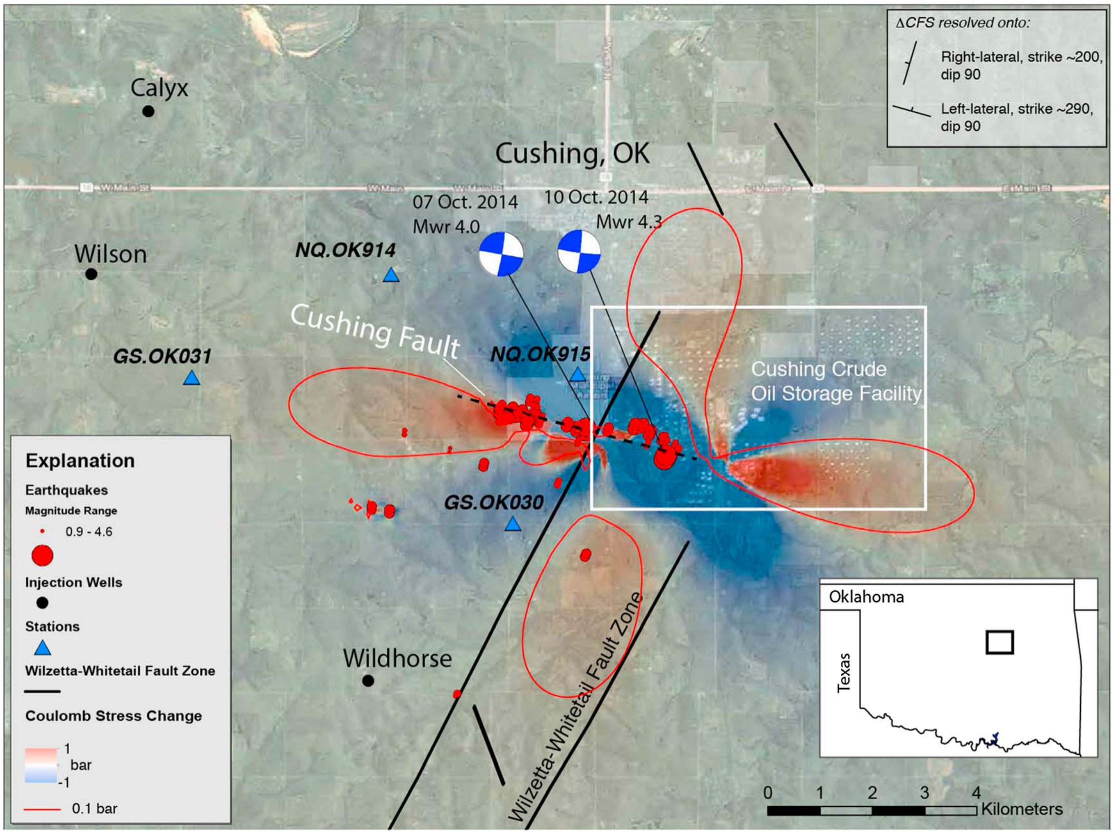

Figure 1. Map of the Cushing Oklahoma region with earthquakes (red circles) seismic stations (blue triangles) and Coulomb failure stress (ΔCFS) model. Strands of Wilzetta-Whitehorse fault zone are shown as black lines. Dashed lines show the conjugate Cushing fault inferred from the spatial distribution of seismicity. *Basemap imagery from GeoEye*.

Hypocentroidal Decomposition (HD) multiple-event method [*Jordan and Sverdrup*, 1981] (Table S1). Earthquakes within the Cushing sequence are relatively shallow ($<$6 km) and align along an approximately 5 km long N80W striking fault within the overlying Cambro-Ordovician Arbuckle group and the crystalline basement (see supporting information for additional details).

Combined analysis of the spatial distribution of earthquakes and regional moment tensor (RMT) focal mechanisms indicate reactivation of a subsurface unnamed and unmapped left-lateral strike-slip fault (striking N80W) (herein called the Cushing fault) that is conjugate to the main branch of the Wilzetta-Whitetail fault zone and

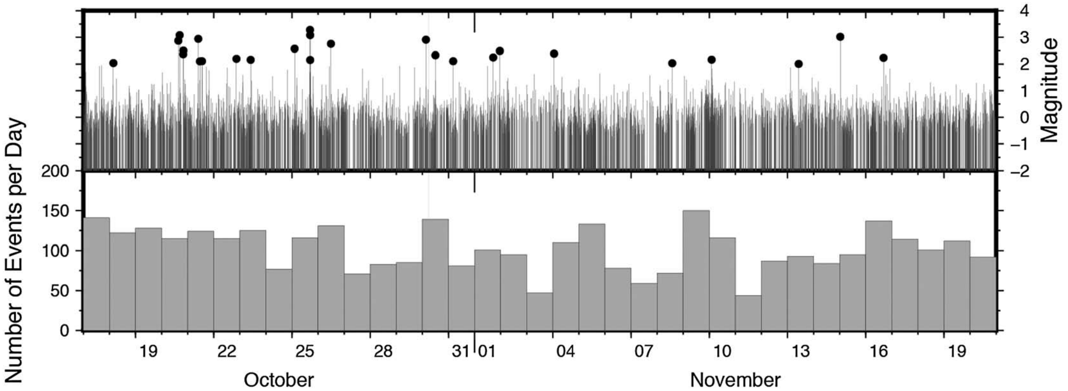

Figure 2. Subspace earthquake detection summary as a function of time for station GS.OK031. (top) The detection magnitudes with earthquakes ($M > 2$) large enough to be detected at multiple seismic stations shown as black circles. (bottom) The number of all detections per day that exceed a 6 sigma threshold above background moving correlation values.

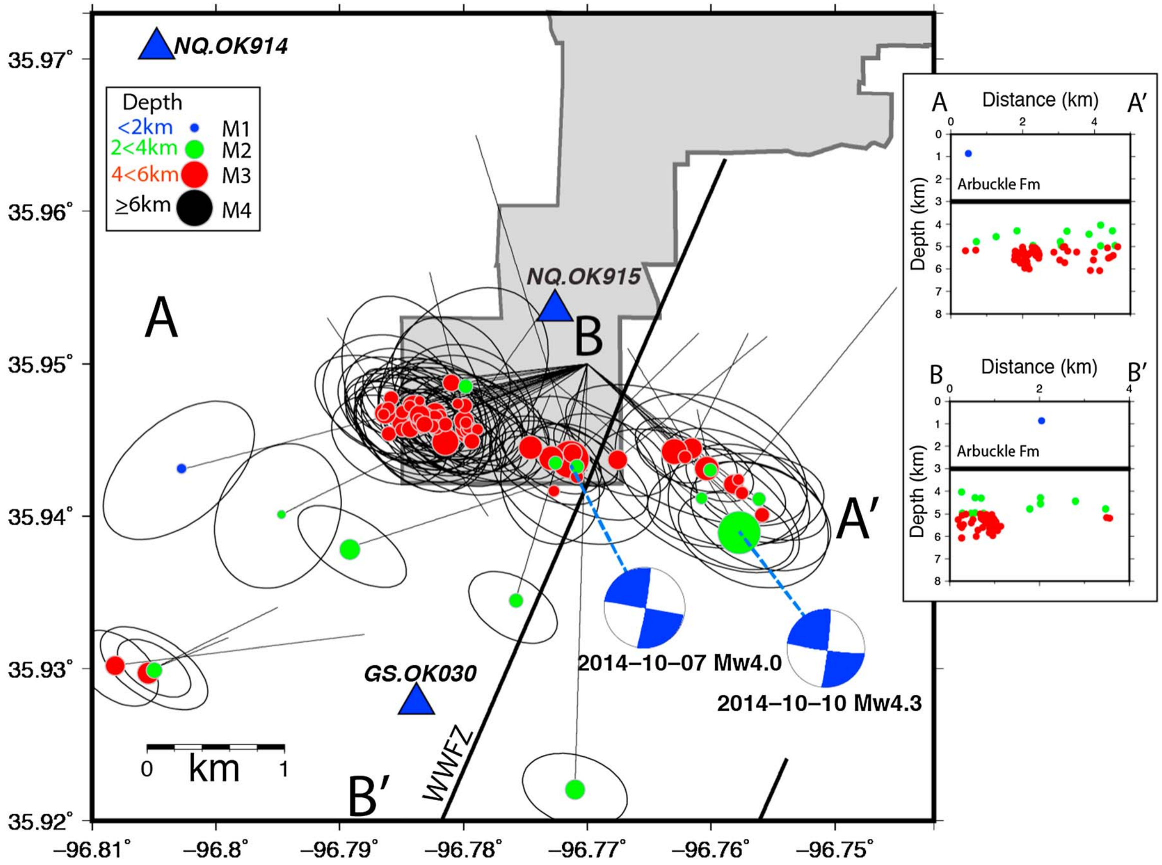

Figure 3. Cushing Oklahoma Hypocentroidal Decomposition (HD) relocated epicenters and *Mw* 4.0 and *Mw* 4.3 left-lateral strike-slip focal mechanisms. Gray region outlines the Cushing city boundary. Circles show the HD relocated hypocenters scaled by magnitude and colored by depth. Blue triangles show the locations of seismic stations used in this study. Thick black lines are subsurface and surface faults of the right-lateral Wilzetta-Whitetail fault (WWFZ). HD uncertainty ellipses and relocation vectors are shown as thin black lines. Relocation vectors for larger magnitude earthquakes originate at the USGS NEIC single-event epicenter or, for smaller magnitude earthquakes, at the starting location determined for all subspace detections. Regional-moment tensors are displayed as blue focal mechanisms. (top inset) Depth profile along strike of the inferred Cushing fault (A-A′). (bottom inset) Depth profile perpendicular to strike of the Cushing fault (B-B′).

has no known historical seismicity [*Northcutt and Campbell*, 1995; *McBee*, 2003; *Bennison*, 1964; *Joseph*, 1987] (Figures 1 and 3). ΔCFS calculations for the Cushing sequence (following *Stein et al.*, 1997; *Stein,* 1999) indicate that the Wilzetta-Whitetail fault zone has, as a result of the recent earthquake sequence, experienced positive static stress changes (>0.1 bar) over a length of at least 8 km south of Cushing (Figures 1 and S2). In addition, increased static stress is modeled on the vertically dipping Cushing fault beyond the ends of the recent earthquakes, and within the shallow basement above the current sequence, over a total length of about 10 km (Figures 1 and S2). Scaling relations suggest that a rupture area of the dimensions that have experienced increased static stress could host earthquakes as large as the 2011 Prague earthquake (*Mw* 5.6) (Figure S4) [*Wells and Coppersmith*, 1994].

Conjugate strike-slip fault systems are common in tectonically active regions such as the western US and have caused large and damaging earthquakes in the recent past. For example, the compound November 1987 Elmore Ranch-Superstition Hills earthquake sequence in southern California demonstrated that rupture on a conjugate strike-slip "cross fault" is capable of triggering rupture on a main fault [*Hudnut et al.,* 1989]. Intraplate regions such as the seismogenic parts of Oklahoma are hypothesized to be in a constant state of failure equilibrium because ductile creep in the lower crust and upper mantle concentrates stress in the upper crust, loading optimally oriented faults to the point of failure [*Zoback and Townend*, 2001; *Zoback and Zoback*, 1991; *Alt and Zoback*, 2014; *Holland*, 2013a]. Positive ΔCFS magnitudes of as little as 0.1 bars (0.01 MPa) have been shown to be sufficient to encourage the occurrence of future earthquakes in regions where faults are critically stressed and close to failure [*Stein*, 1999], as is thought to be the case in much of Oklahoma [*Sumy et al.,* 2014].

In addition to positive ΔCFS increases along the Cushing and Wilzetta-Whitetail fault zones, continued injection of fluids into the fault zone can increase pore pressure and weaken elements of the fault system, potentially leading to rupture [*Healy et al.,* 1968; *Talwani et al.,* 2007]. In the Jones, Oklahoma region, *Keranen et al.* [2014] modeled hydraulic that suggests that small pore pressure perturbations (~0.07 MPa) are sufficient to trigger earthquakes in the Jones Oklahoma region at distances of 10–20 km from high-volume injection wells. Hydraulic fracturing operations used in enhanced oil and gas extraction have also been linked to earthquakes in central Oklahoma [*Holland*, 2013b].

Shortly after the 7 October 2014 Cushing *Mw* 4.0 earthquake, the Oklahoma Corporation Commission (OCC) halted injection operations at three wells (Figure 1) within a 6 mile radius around the main shock epicenter. Inspectors found that the Wildhorse wastewater disposal well was injecting into the basement, below the disposal formation (Arbuckle), which, because of the likely presence of subsurface faults, could greatly increase the potential for inducing earthquakes [*Zoback*, 2012; *Ellsworth*, 2013]. The Wildhorse disposal well was ordered by the OCC to halt operations and plug with cement back up to the depth of the Arbuckle group. Two additional wells in the vicinity (Calyx, Wilson) also experienced short periods of halted operations following the largest earthquakes in the Cushing sequence. All three wells were allowed to resume operations within a few days. The intervals of injection shutdown (10/7 and 10/22) followed by resumption of operations (10/20 and 10/27) correlate with variations in the daily microseismicity rate with a 17 day time lag (Figure S4). Hydraulic diffusivity rates required for the distribution of earthquakes and wells in the Cushing region are consistent with a 17 day lag time and with previous studies in Oklahoma and the central U.S. [*Talwani et al.,* 2007; *Holland*, 2013b; *Keranen et al.,* 2013, 2014; *Kim*, 2013; *Horton*, 2012; *Block et al.,* 2014]. Preliminary observations and hydraulic diffusivity modeling lead us to hypothesize that injected wastewater volume may contribute to the modulation of seismicity rate in the Cushing earthquake sequence (see supporting information for additional details). Most notably, the decline in seismicity correlated with low wastewater volume suggests the potential for earthquake mitigation through managed injection (see electronic supplement for additional detail).

3. Implications for Earthquake Hazard

Earthquakes within the Cushing sequence are of particular interest because of their proximity to critical energy industry infrastructure. Based on results from this study and the similarity of the conjugate strike-slip fault systems in Cushing and Prague, we suggest that a moderate-magnitude (M_w 5.6) earthquake, similar to the 2011 Prague earthquake (M_w 5.6), could occur at the conjugate fault intersection directly beneath the Cushing oil storage facility. The Oklahoma Geological Survey (OGS) reports that the immediate vicinity of the 2011 Prague M_w 5.6 epicenter experienced very strong shaking of intensity levels (MMI VII = 18–34% g) (Okalahoma Geological Survey, 2011, http://www.okgeosurvey1.gov/pages/earthquakes/information.php). Shaking intensity of MMI VII could cause moderate to heavy damage to storage tanks in the Cushing facility depending on the tank height, diameter, and percent full [*O'Rourke and So*, 2000].

It is interesting to note that the felt shaking intensity in the Prague epicentral region was significantly stronger than predicted for central Oklahoma in the USGS National Seismic Hazard Model (NSHM) (2% probability of exceedance in 50 years = 6–10% g) [*Petersen et al.*, 2014]. In the 2014 NSHM, all earthquakes in central Oklahoma were considered induced and thus were not included in the hazard calculations. As a consequence, the recent increased seismicity rate contributes to higher hazard that is not reflected in the NSHM for central Oklahoma. If induced earthquakes are included in the NSHM or if the increased seismicity in Oklahoma over the past several years is a natural process, instead of induced by wastewater injection, maximum shaking levels in the NSHM significantly increase. As a model sensitivity experiment, *Petersen et al.* [2015] included all of the increased seismicity in Oklahoma, including relocated calibrated hypocenters from *McNamara et al.* [2015] and this study in a 1 year NSHM. Inclusion of all recent Oklahoma earthquakes in the NSHM significantly increases ground shaking estimates and earthquake hazard (0.04% probability of exceedance in 1 year = 50–200% g = MMI X+), which would result in serious implications for infrastructure design standards.

4. Conclusions

Based on stress changes due to the 2014 Cushing sequence and continued wastewater injection, we hypothesize that the Cushing and Wilzetta-Whitetail fault zones are critically stressed in a region sufficient enough to increase the likelihood of a large and damaging earthquake similar to the 2011 Mw 5.6 Prague earthquake.

The combination of high-resolution seismicity methodologies with Coulomb stress analysis and with empirical and/or modeled seismicity response due to well-monitored injection volumes offers a path forward toward effective and economically valuable coupled operational earthquake forecasting and associated injection well management in regions of significant induced seismicity.

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