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

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Key Points

Cushing Oklahoma seismicity has transferred stress to faults capable of larger earthquakes

A high degree of potential earthquake hazard exists for communities and energy industry infrastructure near Cushing Oklahoma

Analysis of the October 2014 Cushing sequence and its relationship to wastewater injection is important in order to understand potential hazard to critical infrastructure in the region.

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 (RMT) focal mechanisms indicate reactivation of a subsurface unnamed and unmapped left-lateral strike-slip fault. Coulomb failure stress change calculations (**Δ**CFS), using the relocated seismicity and slip distribution determined from regional moment tensors, demonstrate that the Wilzetta-Whitetail fault zone south of Cushing, Oklahoma, could produce a large, damaging earthquake comparable to the 2011 Prague event. Resultant severe shaking levels (MMI VII-VIII) in the epicentral region present the possibility of this potential earthquake causing damage to national strategic infrastructure and local communities.

Index Terms

7200 SEISMOLOGY, 7215 Earthquake source observations, 7230 Seismicity and tectonics

Key words

Oklahoma seismicity, injection-induced earthquakes, reactivated faulting

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 [**DOT**]. 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 (**Δ**CFS).

The October 2014 Cushing earthquake sequence was significant enough for 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 USGS Did You Feel It system reports that the Mw 4.3 was widely felt up to 210 km north in Wichita, KS, and 240 km east in Fayettville, AR [**USGS DYFI**]. 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, 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, an assessment 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.

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 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-Ordivician Arbuckle group and the crystalline basement (**See electronic supplement for additional detail**).

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 has no known historical seismicity [**Northcutt and Campbell, 1995; McBee, 2003; Bennison, 1964; Joseph, 1987**] (**Figures 1 and 3**). **Δ**CFS 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) [**Wells and Coppersmith, 1994**].

If the Wilzetta-Whitetail fault zone were to rupture beyond the region of increased stress into the active structures extending south of Cushing, the possibility of a significantly larger and damaging earthquake exists (**Figure S3**). 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, 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 Townsend, 1991; Zoback and Zoback, 1991; Alt and Zoback, 2014; Holland, 2013a**]. Positive **Δ**CFS 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 **Δ**CFS 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**]. For example, **Keranen *et al*., [2014]** demonstrated with hydraulic diffusivity modeling 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 event, the Oklahoma Corporation Commission (OCC) halted injection operations at three wells (**Figure 1**) within a six-mile radius around the mainshock 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, can 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 back 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 US [**Talwani *et al*., 2007; Holland, 2013b; Keranen *et al.*, 2013; Keranen *et al.*, 2014; Kim, 2013; Horton, 2012; Block *et al*., 2014**]. Preliminary observations and hydraulic diffusivity modeling, lead us to suspect that injected wastewater volume contributes to the modulation of seismicity rate in the Cushing earthquake sequence (**see electronic supplement for additional detail**).

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 observed shaking during the 2011 Prague M5.6, the Department of Homeland Security (DHS), whose responsibility it is to monitor critical national strategic infrastructure, recognized the hazard posed to the Cushing oil storage facility. For this reason, the newly identified Cushing fault was used by the DHS to compute a USGS PAGER/ShakeMap scenario for emergency response planning purposes at the Cushing storage facility. Assuming a moderate magnitude, similar to the 2011 Prague earthquake (Mw 5.7), the USGS PAGER scenario models maximum shaking of MMI VII that could seriously damage storage tanks and pipelines in the Cushing facility [**Leith, *et al*., 2015**].

The USGS PAGER model modeled that an area of approximately 65 km^2 in the immediate vicinity of the 2011 Prague Mw 5.6 epicenter experienced severe shaking of intensity levels (MMI VIII = 34-65%g) [**USGS PAGER**]. 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 were not included in the hazard calculations. As a consequence, shaking potential is underestimated in central Oklahoma. If policy changes and 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 will 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 has serious implications for infrastructure design standards.

Conclusions

Based on stress changes due to the 2014 Cushing sequence, and continued wastewater injection, it is reasonable to conclude 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. Results from this study can be used as guidance to the recommendation [**Zoback, 2012**] that the energy industry should "avoid injection into active faults" and be prepared to distribute the volume across wells, and/or be prepared to abandon wells altogether in areas of unacceptable risk. The coupling 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 towards effective and economically valuable coupled operational earthquake forecasting and associated injection well management in regions of significant induced seismicity.

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Software used in this study includes GMT and ArcMap to generate maps [**Wessel and Smith, 2004**], SAC for data analysis and time series plots [**Goldstein and Snoke, 2005**] and MAPSEIS/ZMAP for earthquake FMD and Omori's law calculations [**Weimer, 2001**]. All other analysis software was written by the authors.

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Figures

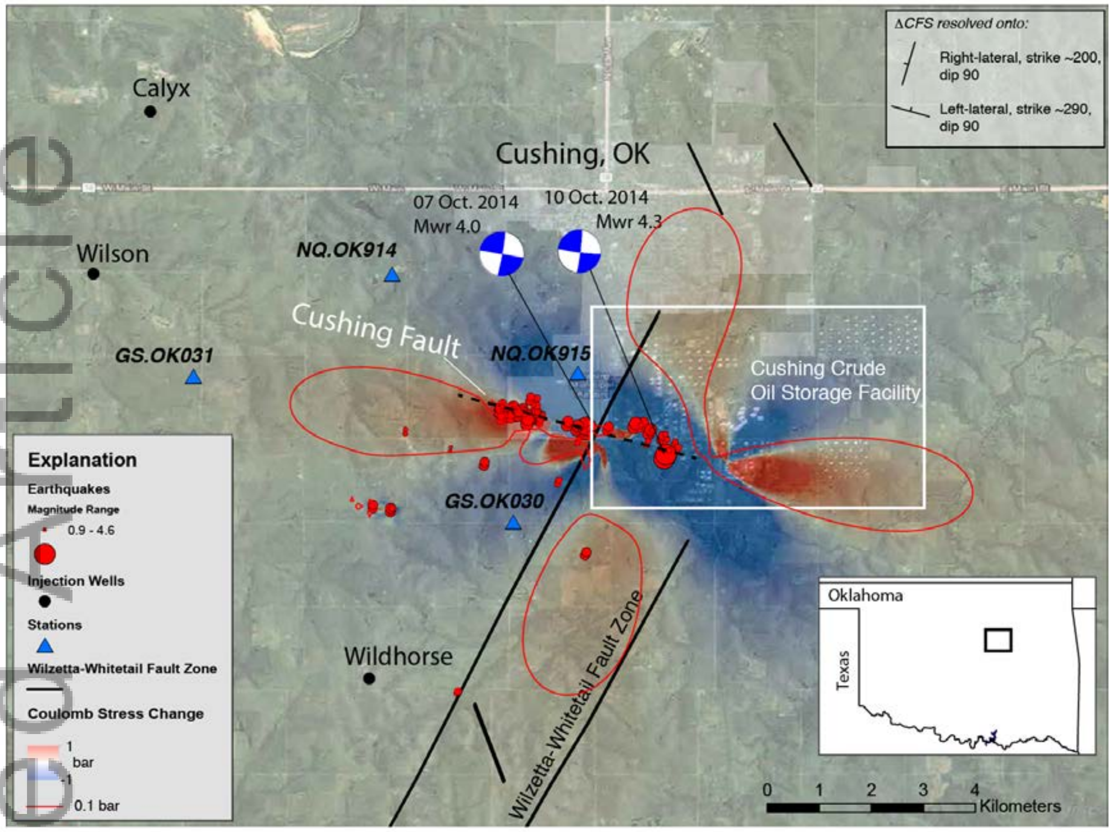

Figure 1: Map of the Cushing Oklahoma region with earthquakes (red circles) seismic stations (blue triangles) and Coulomb failure stress (ΔCFS) model. Strands of Wilzetta-Whitehorse fault zone are shown as black lines. Dashed lines show the conjugate Cushing fault inferred from the spatial distribution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

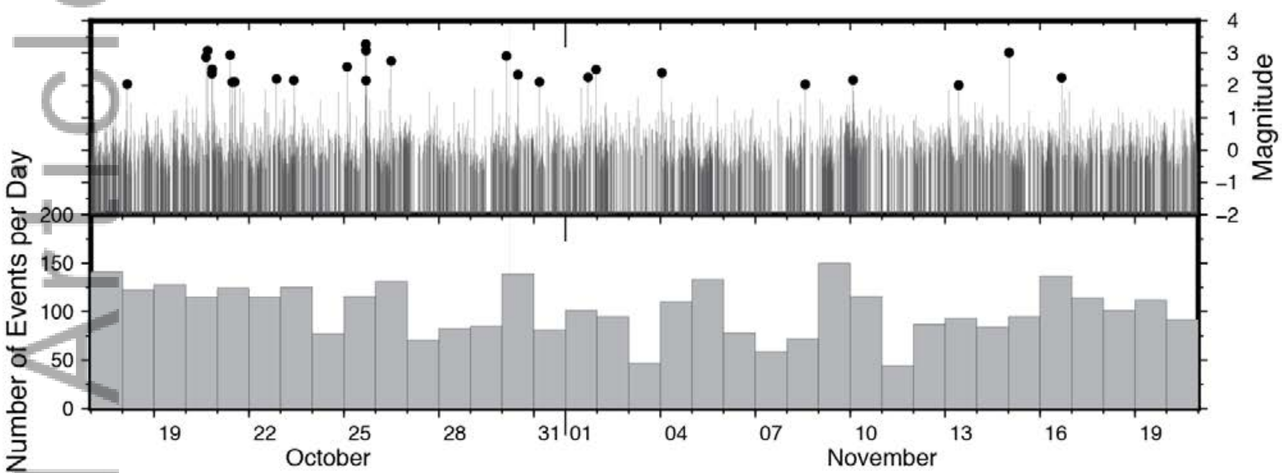

Figure 2: Subspace earthquake detection summary as a function of time for station GS.OK031. The top panel shows the detection magnitudes with earthquakes (M>2) large enough to be detected at multiple seismic stations shown as black circles. The bottom panel shows the number of all detections per day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

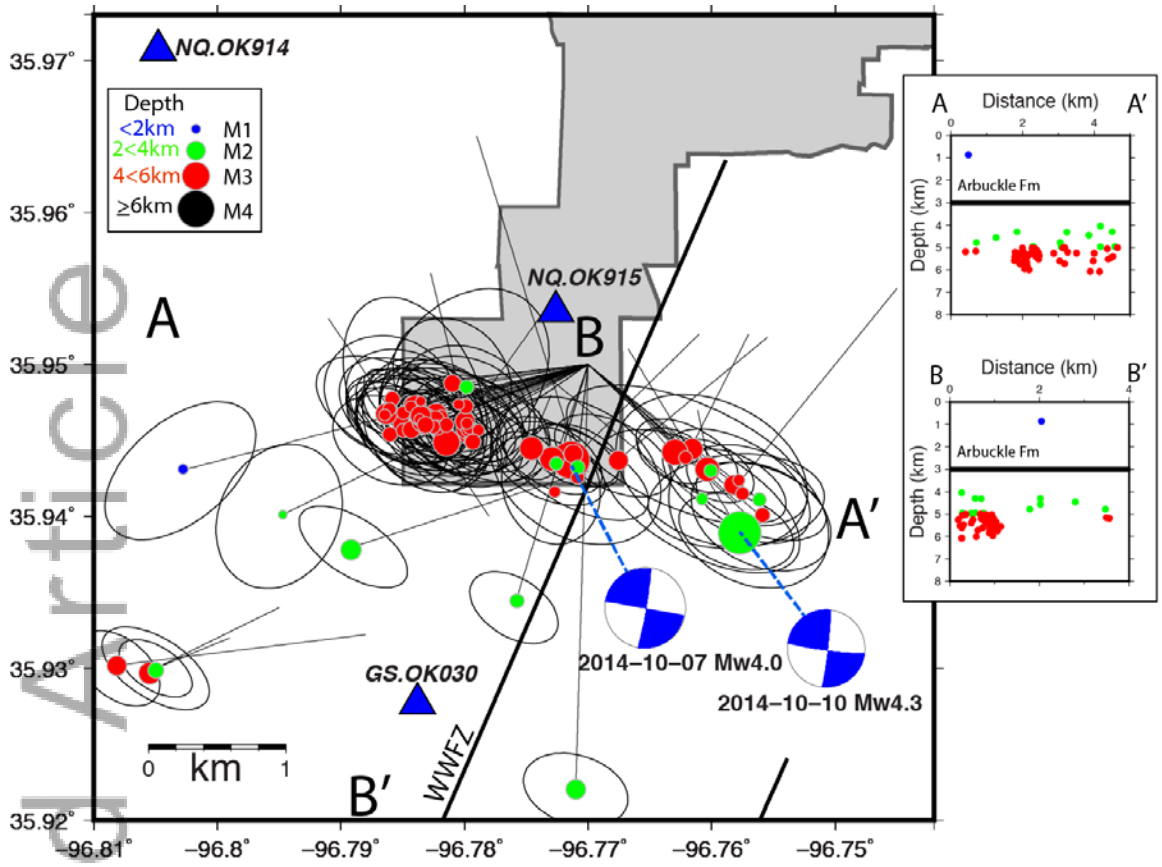

Figure 3: Cushing Oklahoma Hypocentroidal Decomposition (*HD) re-located epicenters and Mw 4.0 and Mw 4.3 left-lateral strike-slip focal mechanisms. Grey region outlines the Cushing city boundary. Circles show the HD relocated hypocenters scaled by magnitude and colored by depth. Blue triangles show 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').*