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Oklahoma's coordinated response to more than a decade of elevated seismicity

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ABSTRACT

In the period between 1961 and 2008, Oklahoma, USA, averaged about two M ≥3.0 earthquakes per year, with no damage to any built infrastructure. A substantial increase in seismic activity was first observed in 2009, when there were 20 M ≥3.0 earthquakes, and activity peaked in 2015, when over 900 M ≥3.0 earthquakes occurred. Because of the unprecedented increase in seismic activity, the governor's office of Oklahoma formed a Coordinating Council of researchers, regulators, industry, and other stakeholders in 2015. The Coordinating Council was led by the Secretary of Energy and Environment and charged with understanding and attempting to mitigate (that is, reduce, if not eliminate) induced seismicity and potential impacts. Major outcomes of the coordinated efforts included delineation of an area of interest (AOI) for seismicity in Oklahoma, modifications to underground injection control (UIC) well completion depths and injection rates into UIC wells in the AOI, development of the Oklahoma Well and Seismic Monitoring (OWSM) application used for regulatory oversight and action, modified well completion protocols, a more robust seismic network, and numerous scientific investigations and publications.

Because of concerted efforts between regulators and industry, disposal into the Arbuckle Group, the primary zone for wastewater disposal, in the AOI was reduced by more than 50% though oil production continued to increase. Seismic activity decreased over a 6 yr period with 619, 302, 195, 65, 39, and 29 M ≥3.0 earthquakes occurring in 2016, 2017, 2018, 2019, 2020, and 2021, respectively. At the time of latest updates to this chapter (16 October 2022), there have been 12 M ≥3.0 earthquakes and one M ≥4.0 earthquake, so the projected total of M ≥3.0 earthquakes in 2022 is

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17. Using these metrics, the coordinated efforts of Oklahoma stakeholders appear to have successfully reduced seismicity with respect to frequency and number in the range of minor but often felt (M 3.0–3.9), light (M 4.0–4.9), and moderate (M 5.0–5.9) earthquakes. So, the Oklahoma case provides examples of how stakeholder action diminished seismic hazards and how similar actions could be used to reduce induced seismicity in other areas where injections occur.

INTRODUCTION

Since the onset of increased seismicity in Oklahoma in 2009 and continuing into the present, the state agencies of Oklahoma have worked together with numerous stakeholder groups, including the academic, regulatory, and industrial communities, to understand and subsequently implement policies to mitigate (that is, reduce, if not eliminate) seismic activity in Oklahoma. Seismicity rates in Oklahoma were markedly increased in 2009 above background, but the initial responses of these separate groups were relatively uncoordinated and independent from one another. However, after the 6 November 2011 Mw 5.7 Prague, Oklahoma, earthquake, the stakeholder groups began to work together to collectively understand and mitigate seismicity. The series of events and actions in Oklahoma may serve as examples for steps that can be taken to mitigate seismic hazard in other regions that are potentially experiencing fluid injection–induced seismicity. This chapter presents a time line and summary of the key state-agency steps that were taken as well as the scientific studies of Oklahoma earthquakes. Major time-line events are summarized in Figure 1, with a focus on Oklahoma from 2009 through the end of 2022.

SEISMIC MONITORING

Records of seismicity in Oklahoma date back to the late 1800s, with the first cataloged earthquake being a M 4.9 event in 1882. Hough and Page (2016) reexamined historical eyewitness accounts of the 1882 earthquake and adjusted the magnitude to M 4.8 and the location, suggesting that the event occurred in southeastern Oklahoma. We generically refer to Richter magnitudes with an M unless a moment magnitude (Mw) was computed from a robust network of seismometers. In addition, several early events in the Oklahoma Geological Survey (OGS) earthquake catalog (Walter et al., 2020) were documented from historical accounts and do not have an estimated magnitude. For example, three felt (estimated to be M ≥3.0) earthquakes in 1900–1901 were reported near Cushing, Oklahoma, which preceded any nearby drilling but led to early oil drilling speculation (Wells, 1985). The OGS operated seismographs that recorded data to paper beginning in the 1960s (Lawson and Luza, 1995). OGS staff would monitor the recordings, identify regional body waves, and share those data with other agencies.

Early Instrumentation (1961–2009)

Early regional events were identified on a seismograph installed at Leonard, Oklahoma, by the Jersey Production Research Company, which later donated the site and equipment to OGS. A network of seismometers was deployed beginning in the late 1970s to systematically measure, locate, and document seismicity in the state. There were about eight permanent seismographs operated by the OGS from 1976 to 2010.

Modern Digital Seismic Network (2010–2022)

Increased seismicity in 2009 prompted the OGS to employ a seismologist in 2010 to expand the seismic network and establish a seismicity research program in Oklahoma. The initial seismicity studies in the modern digital seismic network era leveraged the USArray Transportable Array that was installed across Oklahoma in 2009–2012 (Fig. 2A). Those stations consisted of broadband sensors installed in a grid across the United States at ~70 km spacing. As the seismic activity increased over the ensuing years, researchers from local universities and the U.S. Geological Survey (USGS), along with industry entities, deployed other seismic networks in Oklahoma in response to the increased activity or event magnitude. The OGS seismic monitoring program was expanded further, utilizing data from over 100 seismic stations, from 2013 to 2022 (Fig. 2B) to build and maintain the OGS Earthquake Catalog (https://www.ou.edu/ogs/research/earthquakes/catalogs). The increased density of seismic stations allowed the OGS to reliably detect and locate earthquakes of M ≥2.2 within Oklahoma from mid-2014 to 2022; therefore, M 2.2 represents the "magnitude of completeness" for the OGS catalog. In other words, the earthquake catalog is considered complete for M ≥2.2 earthquake epicenters located in Oklahoma (Walter et al., 2020). Custom OGS-developed open-source software that implements machine learning has increased the detection capability of the network by a factor of two, with more M <2.2 events being detected within the same network footprint (Walter et al., 2021).

SEISMICITY

The U.S. Advanced National Seismic System (ANSS) ComCat catalog reports minor, though often felt, earthquakes that are M ≥3 or larger consistently through time after 1973, although the

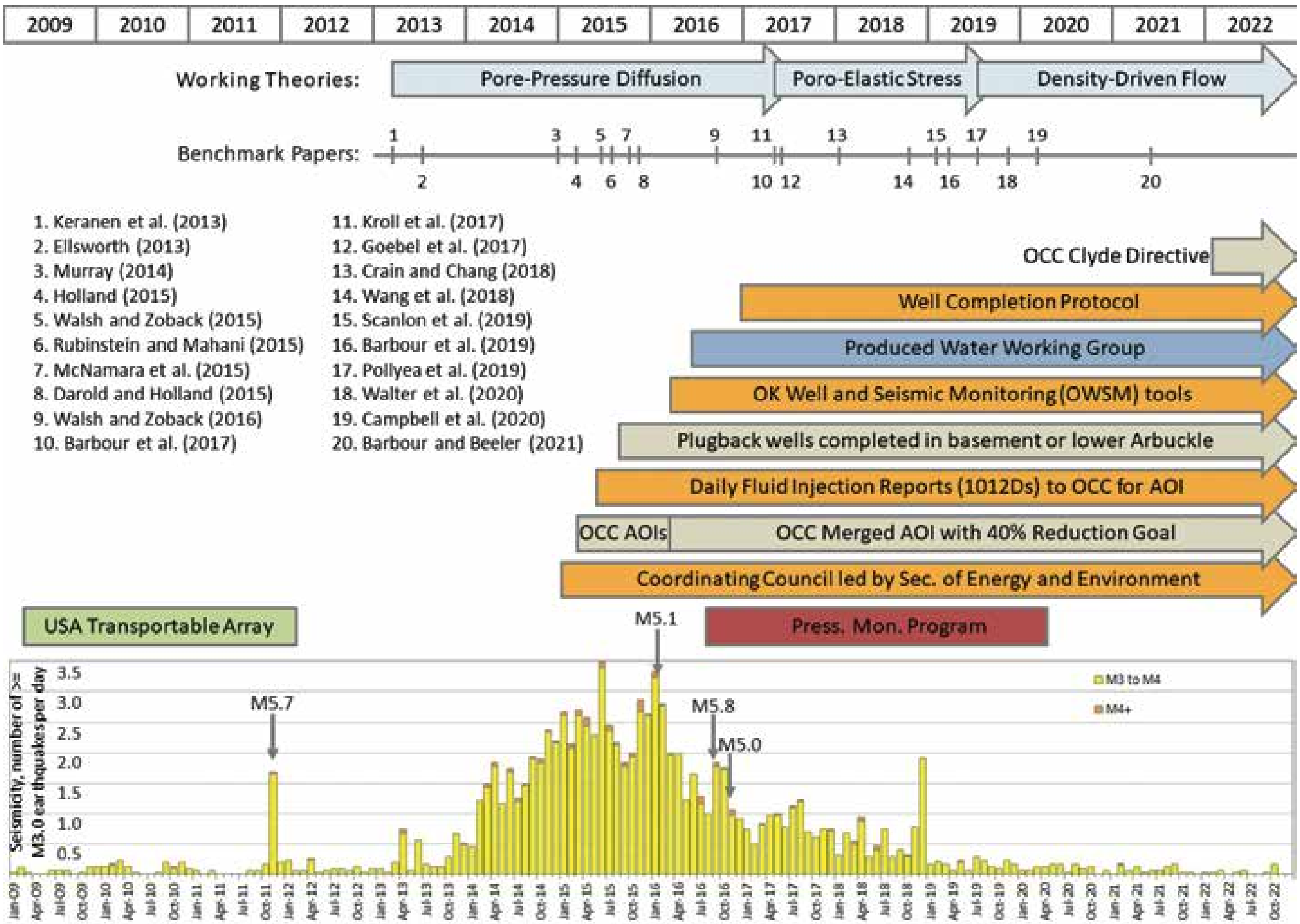

Figure 1. Time line of notable seismic events, benchmark science, and coordinated measures for mitigating seismicity in Oklahoma (OK) from 2009 to 2021. OCC—Oklahoma Corporation Commission; AOI—area of interest; Press. Mon.—pressure monitoring.

spatial location may be uncertain to 5–15 km. The magnitude threshold of M ≥3 provides a benchmark over which we can reliably and consistently track and compare seismicity in Oklahoma over the early instrumentation period and the current local network operation period.

The M ≥3 seismicity rate during the early instrumentation period (1961–2009) was almost two events per year (Walter et al., 2020). This rate is commonly referred to as the background seismicity and represents, in most cases, the natural earthquake activity of the region. Some early seismicity in the 1950s could have been induced by wastewater disposal practices (Hough and Page, 2015), though the pre-1961 record is broadly incomplete and imprecise. Starting in 2009, the seismicity rate (M ≥3.0) began to increase above the background level (Figs. 1 and 3). In the first 4 years, the seismicity rate increased to tens of events per year before increasing to hundreds of events per year in the subsequent 5 years. Seismicity in Oklahoma peaked in 2015, with 901 M ≥3.0 earthquakes recorded in that year, before the rate steadily decreased, with 29 events M ≥3.0 recorded in 2021.

In Oklahoma, there were 12 M ≥4.0 earthquakes from 1882 to 2008 and only one M ≥5.0 earthquake before 2009. Comparatively, there were 95 M ≥4.0 earthquakes and four M ≥5.0 earthquakes from 2009 to 2021 (Figs. 1 and 3). There was one earthquake with M ≥4.0 in 2022, as of the last update (16 October) to this chapter, with a M_L 4.5 event occurring near Clyde in Grant County, Oklahoma, on 31 January 2022. Three of the M 5.0+ earthquakes occurred in 2016, a year after the peak in the seismicity rate of M ≥3.0 earthquakes.

We present a brief synopsis for the historically significant, M ≥5.0, earthquakes in Oklahoma's earthquake catalog. The 9 April 1952 El Reno M 5.5 earthquake was the only M ≥5.0 earthquake prior to 2009 in the OGS earthquake catalog, so it was the largest-magnitude historical earthquake at the time of its occurrence. The El Reno earthquake toppled chimneys in the area west of Oklahoma City and broke windows and dishes. It was reported that it even triggered a landslide in eastern Oklahoma (Regmi and Walter, 2020). Hough and Page (2015) suggested that the occurrence of the event was preceded by adjacent

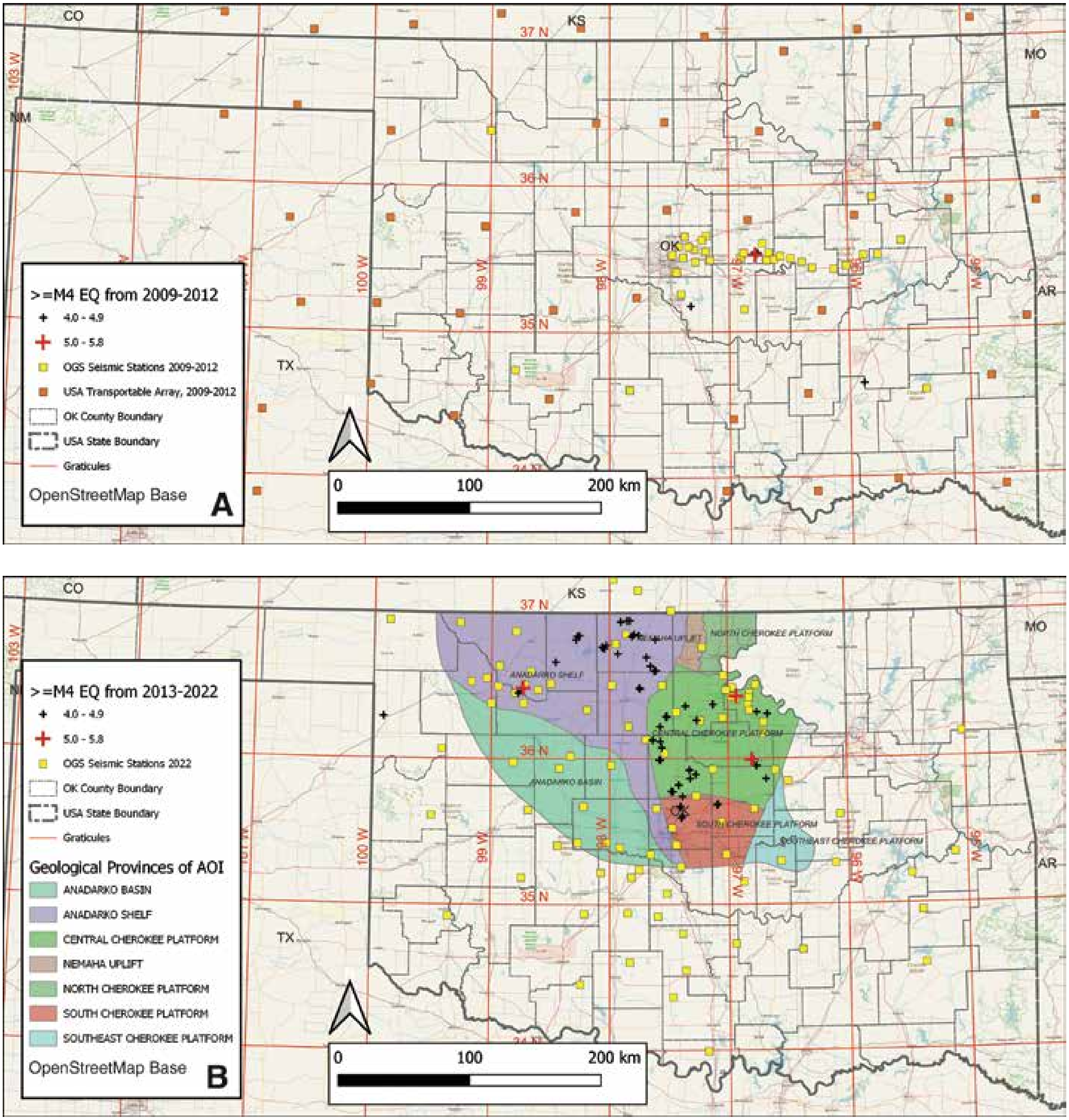

Figure 2. (A) Map of seismic stations that were active within 2009–2012 and ≥M 4 earthquakes (EQ) from 2009 to 2012. OGS—Oklahoma Geological Survey; AOI—area of interest. (B) Map of seismic stations that were active in 2022 and ≥M 4 earthquakes from 2013 to 2021. State abbreviations: CO—Colorado; NM—New Mexico; KS—Kansas; MO—Missouri; AR—Arkansas; OK—Oklahoma; TX—Texas.

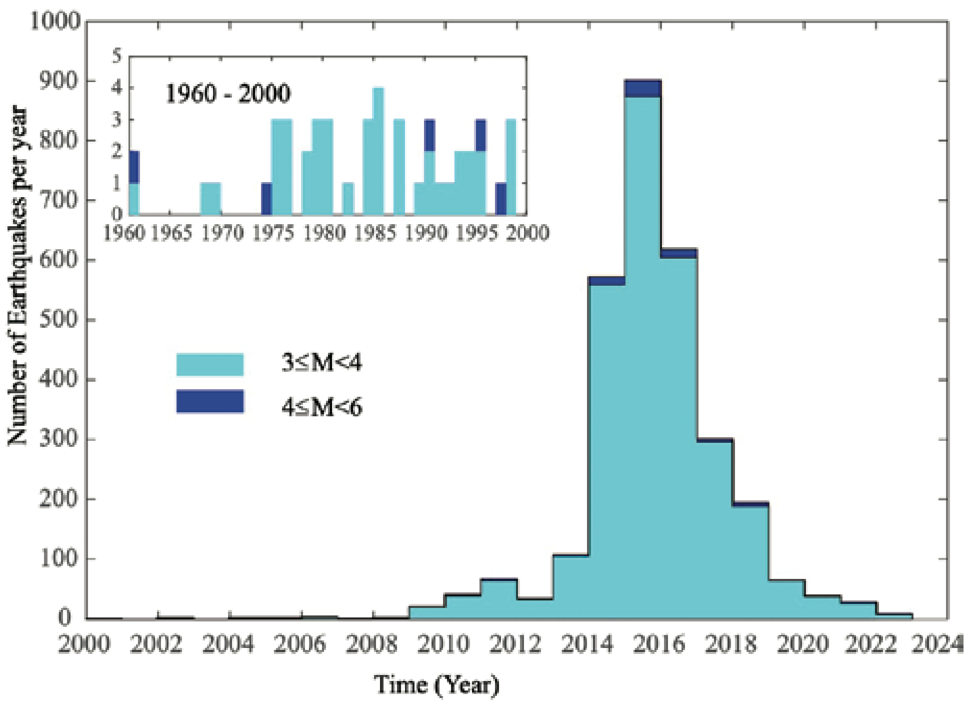

Figure 3. Comparison of seismic events of 3 ≤ M < 4 (cyan) and 4 ≤ M < 6 (blue) per year in Oklahoma for the periods 2001–2023 and 1960–2000 (inset).

disposal operations, though the disposal records were scant at that time, and correlation of disposal to seismicity is difficult given the lack of data.

The 6 November 2011 Prague, Oklahoma, Mw 5.7 earthquake was originally reported as an Mw 5.6 by USGS but was later adjusted in 2016 to be an Mw 5.7 upon recalculation of the W-phase moment tensor. At the time of its occurrence, it was the largest documented Oklahoma earthquake. The earthquake occurred along a splay of the Wilzetta fault and was preceded by a strong Mw 4.8 foreshock ~20 h prior. The foreshock likely triggered the main shock (Sumy et al., 2017), and the scientific community posited nearby wastewater disposal as being correlated in time and space to the foreshock (Holland, 2013; Keranen et al., 2013).

The Fairview Mw 5.1, sometimes also called the Galena Township, earthquake occurred in Woods County on 13 February 2016. It occurred to the NE and in line with a mapped fault, if the fault were extrapolated to the NE from its mapped location (Darold and Holland, 2015). The largest event occurred amidst a seismic swarm, i.e., an increase in seismicity that does not show a clear main shock–aftershock sequence (Eyre et al., 2020), that was plausibly initiated by wastewater disposal greater than 20 km from the epicenter (Yeck et al., 2016). At the time, this was the first documented evidence that wastewater disposal might plausibly induce seismicity tens of kilometers from high-rate disposal wells, rather than the previously documented few kilometers (Weingarten et al., 2015).

On 3 September 2016, the Pawnee Mw 5.8 earthquake supplanted the Prague Mw 5.7 event as the largest-magnitude earthquake recorded in Oklahoma. The epicenter of this earthquake was in Pawnee County at the junction of three separate faults, with only one fault being previously mapped. The correlation of earthquake activity and wastewater disposal volumes (Chen et al., 2017), broadly observed precursory seismicity (Walter et al., 2017), and poroelastic modeling (Barbour et al., 2017) suggested that wastewater disposal could have induced this event.

The Cushing Mw 5.0 earthquake occurred on 7 November 2016 in Payne County and led to considerable damage in the historic downtown area. The damaging main shock occurred along a strike-slip fault that was conjugate (i.e., same age and deformational episode) to a nearby fault that was active 2 yr prior (McNamara et al., 2015).

COORDINATED EFFORTS

Awareness and concerns regarding seismic hazard became more prominent following the November 2011 Prague earthquake, which accelerated action at the state agency level. Because the citizens of Oklahoma were experiencing “felt” earthquakes with some regularity, stakeholders began to exchange information and recognize the public interest and need for concerted actions.

Governor’s Coordinating Council

In September 2014, Governor Mary Fallin enlisted Michael Teague, the Secretary of Energy and Environment (SEE), to assemble a Coordinating Council of representatives from state agencies, academia, nongovernmental organizations, and industry. The mission of the Coordinating Council was to promote communication between stakeholders and take appropriate actions to mitigate seismic hazard in Oklahoma. Monthly Coordinating Council meetings were regularly attended by representatives from numerous organizations, including the SEE, Oklahoma Corporation Commission (OCC), OGS, Oklahoma Independent Petroleum Association (OIPA), Oklahoma Oil and Gas Association (OKOGA), Oklahoma Water Resources Board (OWRB), Oklahoma Energy Resources Board (OERB), Groundwater Protection Council (GWPC), University of Oklahoma (OU), Oklahoma State University (OSU), and University of Tulsa (TU). Seismic activity, research findings, industrial activities, and regulatory concerns were discussed and debated at Coordinating Council meetings.

Oklahoma Seismicity Workshops

Four workshops were held in Oklahoma to bring multiple stakeholder groups together for presentations and discussion of ongoing activities.

The first, the "Fluid Injection Induced Seismicity Workshop," was held in July 2013 at the Moore-Norman Technology Center in Norman, Oklahoma. The goals of the workshop, as described by the OGS Director, were to (1) obtain stakeholder input for developing a best practices document, (2) take advantage of valuable operational and technical experience, (3) identify where supporting information regarding risk analysis and mitigation may be beneficial, and (4) discuss how to provide some public education on the issues.

The second workshop was organized by the USGS and OGS and was convened in November 2014 in Midwest City, Oklahoma. There were ~150 participants at the second workshop, and discussions primarily involved potential annual revisions to the current, as of 2014, USGS 6 yr National Seismic Hazard Model (NSHM).

The third workshop was organized by the OGS and held at the Moore-Norman Technology Center in Norman on 7 and 8 September 2016. Sessions included (1) Networks and Monitoring, (2) Data Acquisition and Management, (3) Fluids and Pressure, (4) Seismological Data Analysis, (5) Geological and Reservoir Characterization, (6) Structure and Stress, (7) Hazards and Ground Motion, and (8) Engineering and Built Environment.

The fourth workshop, organized by the OGS, was held on 21 and 22 February 2018 at the National Center for Employee Development (NCED) in Norman. Sessions included (1) Spirit of Collaboration, (2) Earthquake Catalogs in the Mid-Continent: A Closer Look, (3) Is it Possible to Differentiate Natural from Induced Seismicity? (4) Geophysical Characterization, (5) Geological and Reservoir Characterization, (6) Structure and Stress, (7) Regional and Play-Based Analysis of Brine Management Versus Seismicity, (8) Pressure Propagation and Poroelastic Stress, (9) Hydraulic Fracturing and Mitigation Strategies, and (10) Hazards, Engineering, and the Built Environment.

Presentations of research findings, regulatory measures, and industrial responses were given and discussed among the workshop participants. Each workshop was valuable because stakeholders from Oklahoma interacted with their counterparts from other regions, exchanged the state of understanding of seismicity in the southern midcontinent, shared lessons learned within the stakeholder community, opened lines of communication, and promoted future collaborations.

SCIENTIFIC RESEARCH

There has been an abundance of scientific research related to seismicity in the United States, the midcontinent, and specifically to seismic activity in Oklahoma. In the sections that follow, we provide a brief annotated summary of publications that were, to our knowledge, among the first to present new data or concepts that have shaped our understanding of seismicity, related activities, and the geologic framework of Oklahoma. For example, Ellsworth (2013) highlighted the increase in seismicity in the United States and proposed that earthquakes are more frequently induced by increasing fluid pressure promoting slip on a preexisting fault.

Associations between Seismicity and Saltwater Disposal

The Arbuckle Group was formed during the late Cambrian and Early Ordovician when the southern midcontinent was covered by a shallow sea. It underlies nearly all of Oklahoma and Kansas and extends into other states in the southern midcontinent, including Texas, where it is referred to as the Ellenburger Group. The Arbuckle Group is composed mainly of limestone and dolostone with some sandstone and shale interbeds. The Arbuckle Group outcrops in uplifted parts of Oklahoma near the Wichita Mountains and Arbuckle Mountains. The Arbuckle Group is part of the Arbuckle-Simpson karst aquifer in south-central Oklahoma, so it may have large pore spaces and high permeability in other parts of the subsurface. In the Anadarko Shelf and Cherokee Platform of central and northern Oklahoma, the Arbuckle Group readily accepts wastewater without applying pressure at the wellhead and is hydraulically separated from underground sources of drinking water (USDW), which historically made it an attractive target for saltwater disposal (SWD) as part of the Underground Injection Control (UIC) program.

Keranen et al. (2013) were the first to report the Mw 5.7 Prague, Oklahoma, earthquake as potentially induced by injection of wastewater (i.e., water coproduced with oil and gas) into the Arbuckle Group, with the bounding faults of a fault block forming effectively sealed compartments. Murray and Holland (2014, p. 98) identified the Arbuckle Group as the primary SWD zone in Oklahoma, described the Arbuckle as having "an unwavering capacity to accept fluids without any observed increases in pressure," and reported over 400 million barrels of SWD injected into the Arbuckle Group of Oklahoma during 2011. Walsh and Zoback (2015) illustrated that increases in minor- to moderate-sized earthquakes occurred following increased SWD rates into sedimentary formations that appeared to be in hydraulic communication with potentially active faults in crystalline basement.

Few researchers had quantified the strength of correlation between seismicity and SWD volumes or rates because SWD data were limited in the 2009–2015 time frame. However, after 2015, the SWD data were available, so a Pearson product moment correlation coefficient (*r*), which is a measure of the relationship between a dependent variable (i.e., *y* value) and an independent variable (i.e., *x* value), could be calculated for seismicity (*y* values) versus SWD (*x* values). The *r* value is often squared to derive a coefficient of determination, or R^2 value, which ranges from 0 to 1, where an R^2 of 0 indicates no correlation, and an R^2 of 1 indicates the strongest possible (i.e., perfect) correlation (Legates and McCabe, 1999). Chen et al. (2017) reported that cross-correlation of Arbuckle injection rate versus seismicity rate had a maximum R^2 of 0.91 with a time lag of 300 days. Scanlon et al. (2019) statistically associated seismicity in Oklahoma to SWD rates, cumulative SWD volumes, and proximity of injection to basement.

Fault Networks and Fault Failure

The Arbuckle Group is underlain by the Southern Granite-Rhyolite Province in the U.S. midcontinent and has undergone multiple phases of tectonic deformation, including N-NE/S-SE rifting, reverse faulting, and NW-SE rifting (Kolawole et al., 2019). Oklahoma's principal stresses from intraplate tectonics are contemporaneously directed NW-SE. A fault map of Oklahoma was prepared by Holland (2015) by compiling surface and subsurface faults from the published literature and merging them with faults provided by industry. McNamara et al. (2015) relocated 195 of the largest earthquakes in Oklahoma and determined the length, depth, and style of faulting on the reactivated fault systems. Results showed that most earthquakes occurred on near-vertical, optimally oriented (NE-SW and NW-SE), strike-slip faults in the shallow crystalline basement (McNamara et al., 2015). Darold and Holland (2015) presented a map that illustrated the strike of fault segments relative to the results obtained from calculating focal mechanisms of 688 earthquakes in Oklahoma. Faults that are oriented near N85°E are referred to as optimally oriented faults because they are most likely to fail under Oklahoma's contemporary stress field (Darold and Holland, 2015). Walsh and Zoback (2016) used quantitative risk assessment and a cumulative distribution function to calculate probability of slip on faults, with the approach indicating a high probability of failure on the faults that hosted the Prague, Fairview, and Pawnee earthquakes.

Stress Transfer from Fluid Injection

The physical mechanism(s) by which earthquakes are triggered is(are) still uncertain and may never be proven because of our limited ability to measure the state of stress or pressure in the deep basement rocks or on the faults that host earthquakes. Three main theories have been presented in the literature to describe the processes or mechanisms by which fluid injection into the Arbuckle Group could affect the pressure equilibrium along basement faults.

The first mechanism, pore-pressure diffusion, posits an increase in pore pressure in the injection zone (e.g., Arbuckle Group) that could be transferred to a basement fault by diffusion and, thus, trigger an earthquake on a critically stressed and optimally oriented seismogenic fault. Research on Oklahoma seismicity from 2013 to 2015, including that conducted by Keranen et al. (2013, 2014), Weingarten et al. (2015), and Walsh and Zoback (2015), adopted pore-pressure diffusion as the primary mechanism for inducing seismicity in the state.

The second mechanism, poroelastic stress, was presented in 2017 because pore-pressure diffusion alone could not explain triggering of earthquakes that were counter to hydraulic gradients and at great distances from Arbuckle SWD wells (Barbour et al., 2017; Goebel et al., 2017; Kroll et al., 2017). McConville (2018) built a groundwater flow model for a portion of the Anadarko Shelf, which indicated that pore pressure was minimally perturbed by advective processes, or the equivalent of pore-pressure diffusion, at the Fairview Mw 5.1 hypocenter. The McConville (2018) model simulations suggested that another mechanism, other than pore-pressure diffusion, must be acting in the subsurface if stress is transferred from injection wells to a seismogenic fault.

The third mechanism, density differentials, contends that pressure transients caused by density differences between the wastewater and host-rock fluids result in a downward migration of more dense fluid (Pollyea et al., 2019). Oklahoma's oil and gas wells completed in the Mississippian zone are notorious for generating relatively large amounts of produced water, and the Arbuckle zone is the predominant disposal zone for Mississippian produced water. A comparison of Mississippian produced water and Arbuckle formation/produced water epitomizes this density differential: The median total dissolved solids (TDS) concentration of 356 Mississippian samples is 196,061 mg/L, which is much higher than the median TDS of 38,857 mg/L for 11 Arbuckle samples (Murray, 2021). Higher TDS results in a higher fluid density for the wastewater fluids.

Because research (Kroll et al., 2017; Goebel et al., 2017; Barbour et al., 2017) has demonstrated that pore-pressure diffusion and poroelastic stress are occurring simultaneously, it is likely that all three of these mechanisms (and maybe others) are acting simultaneously to influence pressure and the state of stress at seismogenic faults. Regardless of the mechanism or model that is used to link injection to seismicity, a fundamental understanding of the subsurface, including fault plane characteristics, fault style, fault orientation, reservoir and basement properties, and injection fluid characteristics, is essential to properly constrain a model.

Subsurface Rock Properties

Numerous studies have been conducted to measure or inversely model subsurface rock properties in Oklahoma. Carrell

(2014) evaluated drill-stem test data for wells in northern Oklahoma and reported a mean horizontal permeability of 797 mD for the Arbuckle Group. Morgan and Murray (2015) measured small-scale permeability ranging <0.16–115.87 mD for the Arbuckle Group in core and outcrop material using a handheld air permeameter. The small-scale measurements are reportedly most useful as vertical permeability or lower-end limits of the Arbuckle Group permeability (Morgan and Murray, 2015). Perilla-Castillo (2017) used solid Earth tide analyses of fluid-level fluctuations in Arbuckle SWD wells to estimate median specific storage (Ss) of 1.39E-06 m^{-1}, matrix compressibility of 4.35E-05 MPa^{-1} (3.02E-07 psi^{-1}), and intrinsic permeability of 34.37 mD. Williams (2017) used a handheld air permeameter to analyze an Arbuckle core and reported small-scale permeability from 0.22 to 387.2 mD and solid Earth tide analyses of Arbuckle SWD well fluid fluctuations to report a permeability from 285.5 to 1304.7 mD. Kroll et al. (2017) used earthquake parameters to inversely model the strain (i.e., fluid response) at two wells in Payne County. After a grid search, the poroelastic model parameters yielding the best fit included an undrained bulk modulus of 61.9 GPa and 59.1 GPa, a bulk modulus for the fluid of 3.4 GPa and 2.0 GPa, and porosity of 7.44% and 8.67% for the Pawnee and Cushing events, respectively (Kroll et al., 2017). McConville (2018) simulated steady-state and transient pressures in the Arbuckle Group using a MODFLOW model and matched the simulated heads to observed heads in the pressure monitoring network. The best-fit hydraulic conductivity and Ss values were 1.9 m/d and 4.53E-07 m^{-1}, respectively, i.e., one or two orders of magnitude higher than previous estimates (McConville, 2018). Barbour et al. (2019) measured downhole pressure in an Arbuckle SWD well in Osage County and analyzed the response of the fluid to Earth tidal stresses to calculate Ss of the Arbuckle interval to be 2.0E-07 m^{-1} ± 2.0E-08 m^{-1} based on uncertainty of other input parameters. Barbour and Beeler (2021) used the poroelastic responses in the Arbuckle fluid levels to various teleseismic events to show that properties of the Arbuckle Group are anisotropic (i.e., vary with azimuthal direction).

REGULATORY RESPONSE

One of the first regulatory responses was for the OCC to require operators of Arbuckle SWD wells within the AOI to provide a weekly report that compiled the daily injection rates and pressures at the wells. These daily fluid injection reports (Form 1012D) were used by all stakeholders as a near-real-time measure of SWD rates. The OCC then sought to mitigate seismicity by working with operators of SWD wells and companies performing drilling and completion activities mostly within the AOI. With pore-pressure diffusion as the main explanatory mechanism in early 2015, the OCC "directives" attempted to mitigate seismicity in the AOI with two main strategies: (1) directing operators to plug back wells away from the basement, and (2) reducing SWD rates into the Arbuckle zone. Later, in 2016, the OCC developed a protocol to attempt to mitigate seismicity associated with well completion activities.

Plug Back Wells from Basement

In March of 2015, the OCC requested that operators of 347 UIC wells provide documentation of the depth to top of basement and open interval of UIC wells completed in the Arbuckle zone and, if not able to identify the depth to top of basement, plug the well back at least 61 m (200 ft) for wells that ranged in depth from ~1349 to 3290 m (4425–10,793 ft). A typical plug-back procedure involves cementing the deeper portions of an open borehole to close off the basement or Arbuckle Group, which is followed by installation of a cast iron plug, resulting in a shallower total well depth. The goal of plugging back a well is to limit the hydraulic connection between the injection intervals and seismogenic basement faults. Prior to the March 2015 plug-back initiative, ~16 wells were plugged back in a 14 month period from 14 January 2014 to 1 March 2015. The March 2015 directive resulted in an additional 181 wells being plugged back over the next 10 months or by the end of 2015 (Fig. 4). Plug backs continued thereafter, but only 28 plug backs occurred over the next 20 months or through the end of August 2017. In addition to plug backs, some operators chose to recomplete Arbuckle UIC wells into shallower zones. By the end of 2020, a total of 225 Arbuckle wells had been plugged back from basement in the AOI. From 2015 to 2020, an additional 168 wells terminated their UIC authorization to inject into the Arbuckle Group or were recompleted to inject into a shallower zone.

Shut In, Reduce, or Cap Injection Rates for Arbuckle SWD Wells

By the end of 2016, after more than 21 directives, the AOI encompassed 4.2 million hectares (10.4 million acres or 16,203 square miles), colored on Figure 2B, in parts of 29 central and north-central Oklahoma counties. In response to the largest earthquake detected in modern time in Oklahoma, the 3 September 2016 Mw 5.8 Pawnee earthquake, the OCC collaborated with the U.S. Environmental Protection Agency (EPA) to shut in a total of 32 Arbuckle SWD wells and reduce disposal rates at another 35 wells in Pawnee and Osage Counties. (Osage County is under the jurisdiction of multiple federal authorities for oil and gas permitting and environmental response; the EPA manages the Osage UIC permitting.) In a directive issued in March of 2017, the OCC capped injection rates for Arbuckle SWD wells to 15,000 barrels per day (BPD) in the Anadarko Shelf (purple on Fig. 2B) and Anadarko Basin (blue-green on Fig. 2B) and 10,000 BPD in the five geologic provinces east of the Nemaha fault zone in the AOI. In the years following the flurry of actions taken in 2015 and 2016, the OCC issued 10 additional directives affecting Arbuckle SWD wells in Oklahoma. A full history of all actions is available on the web page of the OCC's Induced Seismicity Department (https://

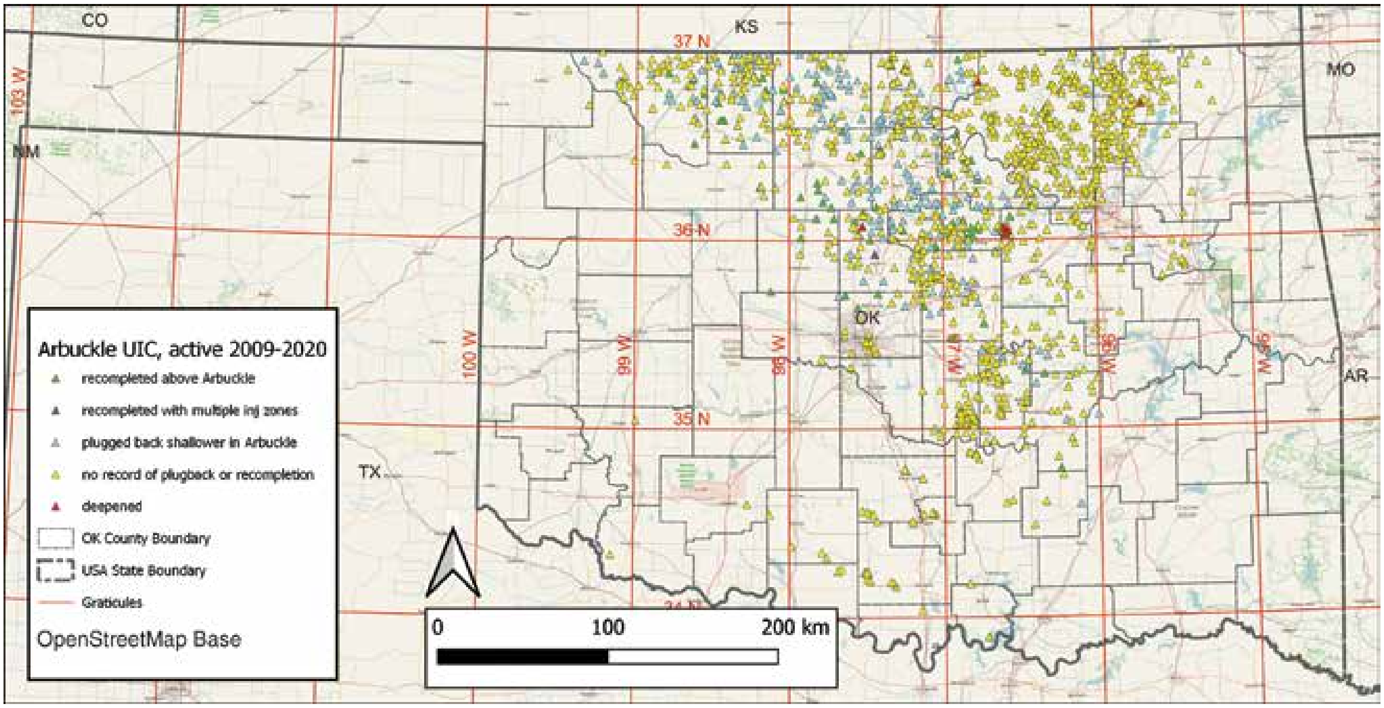

Figure 4. Reported modifications to underground injection control (UIC) wells that were completed in the Arbuckle zone and were active (i.e., injected at least one barrel of saltwater) from 2009 to 2020. See Figure 2 for state abbreviations.

oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/response-oklahoma-earthquakes.html).

Oklahoma Well and Seismic Monitoring Application

Several well-viewer applications (i.e., graphical user interfaces that can illustrate UIC well locations, depths, injection rates, or pressures) have been created over the past decade in various regulatory environments for the dissemination of well data and UIC injection data; however, few included an added seismic element. In late 2015, the GWPC partnered with the OCC and other stakeholders to develop a new application to address the specific needs of the OCC to view and quickly assess induced seismicity concerns in Oklahoma. The Oklahoma Well and Seismic Monitoring (OWSM) application first debuted in March 2016 as a Web-based seismic investigation tool combining high-level geographic information system (GIS) tools and interactive charting with a more traditional well data viewer.

Some benefits of the OWSM application over more traditional well viewers include (1) rapid response to seismic events of interest (24 hours per day; 7 days per week); (2) high-level GIS capability in a Web-based platform with simplistic buffering, charting, and analysis tools; (3) intuitive seismic event-well correlation capabilities, which allow for quick assessment and reaction to induced seismicity hazards; and (4) near-real-time compilation of varied data streams, including injection data, well construction information, and earthquake data, which provides a comprehensive, easily accessible resource with which to assess, analyze, and react to seismic hazards and output graphics for internal and external audiences.

Continued development of the OWSM platform will aid stakeholders in monitoring induced seismic hazards in Oklahoma from a variety of sources. The application has broad potential for application to various data streams and other induced seismic hazards, including carbon capture and sequestration or geothermal injections.

Well Completion Protocol

In December 2016, proactive guidelines were developed for the South-Central Oklahoma Oil Province (SCOOP)–Sooner Trend Anadarko Canadian Kingfisher (STACK) Focus Area to mitigate seismicity that was closely associated in time and space with hydraulic fracturing (HF) and stimulation during well completion. The initial HF protocol was based on seismic activity triggers, with an M 2.5 event triggering the OCC to contact the operator to discuss a mitigation plan, an M 3.0 event triggering the operator to observe a 6 h pause in well completion activities and to have a technical call with OCC regarding mitigations, and an M 3.5 event triggering the operator to suspend well completion activities and to hold a technical meeting with the OCC. A more recent update to the well-completion protocols at the OCC, released in February of 2018, lowered the magnitudes by 0.5, with action being triggered as a result of earthquakes at M 2.0, M 2.5, and M 3.0.

Shut In or Reduce Injection Rates for Arbuckle SWD Wells in 2022

As part of its continuing effort to reduce the risk of seismicity, the OCC Oil and Gas Conservation Division (OGCD) issued a new directive on 31 January 2022 for a portion of the existing AOI. The directive addressed the M_L 4.5 event that occurred on 31 January 2022, northeast of the town of Clyde in Grant County, Oklahoma. Following the directive, seven wells within 10 km (6 miles) of the M_L 4.5 event were shut in, and 15 wells within 10–16 km (6–10 miles) of the M_L 4.5 event were required to reduce disposal volumes to the lesser of 500 BPD or the BPD average injection for the last 30 days reported to OCC on Form 1012D.

SUMMARY

The background seismicity (i.e., prior to 2009) in Oklahoma was about two M ≥3.0 events per year statewide for more than 100 yr since felt earthquakes were documented by residents of Oklahoma preceding the 1889 land run and statehood in 1907. Then, there was a marked increase in seismicity starting in 2009 such that by 2015, there was an astounding 450-fold increase above background annual rates. Oklahoma's largest recorded earthquake during this period of high seismicity occurred in 2011 in Prague with Mw 5.7; this was later superseded by the Pawnee Mw 5.8 event in 2016. These events, 95 other M ≥4.0 events, and thousands of M ≥3.0 earthquakes from 2009 to 2021 dramatically increased the potential seismic hazard, which required a concerted effort, led by members of the governor's Coordinating Council, to mitigate seismicity.

Because the strong correlation between SWD into the Arbuckle Group and seismicity in central and north-central Oklahoma was inarguable, the OCC requested more frequent reporting of SWD injection and three types of actions by operators, including (1) plugging back SWD wells away from basement; (2) shutting in Arbuckle SWD wells in close proximity to M ≥4.0 events and reducing disposal rates into Arbuckle SWD wells, with the goal being to reduce seismicity by more than 40% from the peak rates of 2014 and 2015; and (3) monitoring seismicity and implementing well-completion protocols to mitigate seismicity during hydraulic fracturing operations. A market downturn that occurred in mid-2014, prior to the issuance of directives by the OCC, also affected drilling and completion activities, oil and gas production, and SWD rates. While it is not possible to disentangle the effects of market forces from directives or the efficacy of plugging back wells versus reducing injection rates, the coordinated and intentional action must have been the impetus for the steady decline in seismic activity. The steps taken by Oklahoma stakeholders were effective in mitigating seismicity and may yield valuable lessons for other regions to address similar challenges with induced seismicity.

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