Preface to the Focus Section on the 3 September 2016 Pawnee, Oklahoma, Earthquake

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The M_w 5.8 Pawnee earthquake occurred at 12:02 UTC on 3 September 2016, local time at 6:02 a.m. on Saturday. It was widely felt throughout Oklahoma and neighboring states. The earthquake occurred near the junction of the two previously mapped faults: Watchorn fault and Labette fault. However, the actual source fault was the previously unmapped Sooner Lake fault (also known as the Pawnee fault). This is the largest earthquake since the 1950s in the instrumental history in Oklahoma. Many recent studies suggest that most earthquakes in Oklahoma since 2009 are induced by wastewater injection (e.g., Ellsworth, 2013; Keranen *et al.*, 2014; Walsh and Zoback, 2015), and the Pawnee earthquake is potentially the largest injection-induced earthquake that has occurred so far (Yeck *et al.*, 2016).

This focus section of *Seismological Research Letters* includes 10 original research papers that provide a complete view of the stress evolution leading to the mainshock inferred from foreshock activities and coupled poroelastic modeling; coseismic stress changes and deformations from both seismological and geodetic observations; dynamic hydrological responses at far-field; and liquefaction observations from geoelectrical and surface mapping.

Wang *et al.* (2017) and Kroll *et al.* (2017) investigated hydrological responses due to the M 5 earthquakes in Oklahoma. Among them, Wang *et al.* (2017) observed groundwater level changes over distances greater than 150 km from the epicenter. The model that is most consistent with observation is aquifer recharge due to enhanced crustal permeability produced by seismic waves. Their simulation suggests that the source of recharge was high-pressure chambers near the responding wells, which became hydraulically connected to the well by enhanced permeability during the earthquake. Kroll *et al.* (2017) investigated how the poroelastic properties of the Arbuckle group change laterally and over time. They used observations of fluid level changes at two monitoring wells in response to the Pawnee and the 7 November 2016 M_w 5.0 Cushing earthquakes. Modeling of the fluid level changes from a set of earthquake source parameters and spatiotemporal poroelastic properties of the Arbuckle suggests that both the direction of the observed fluid level change and the amplitude can be predicted from the computed volumetric strain change and a reasonable set of poroelastic parameters. The results also indicate that poroelastic parameters differ at the time of the Pawnee and Cushing earthquakes, with a moderately higher Skempton's coefficient required to fit the response to the Cushing earthquake. Their results suggest that dynamic shaking resulted in physical alteration of the Arbuckle at distances up to ~50 km from the Pawnee earthquake.

Fielding *et al.* (2017), Pollitz *et al.* (2017) and Grandin *et al.* (2017) analyzed the rupture process of the mainshock and surface deformation using InSAR and seismological observations. Pollitz *et al.* (2017) used a combination of InSAR and GPS offsets, while Fielding *et al.* (2017) and Grandin *et al.* (2017) performed joint inversion with both InSAR and seismological data. All the inversions inferred that the left-lateral slip on the Sooner Lake fault was concentrated slightly east and downdip of the hypocenter, and almost all the coseismic slip was within the crystalline basement rock. The inversion suggests that seismic activity, although likely triggered by anthropic activity, is primarily driven by a coherent regional stress field. In addition to the slip model, Pollitz *et al.* (2017) inferred a few decimeters of fault zone collapse, which could represent the migration of large volumes of fluid from the fault zone enabled by temporarily elevated permeability following the mainshock. Fielding *et al.* (2017) suggested that the coseismic slip extended at least 2 km and probably to 12–14 km depth with the hypocenter at roughly 4 km depth.

Cramer (2017) analyzed Brune-type stress parameters for the Pawnee mainshock and other moderate earthquakes in Oklahoma through velocity spectrum analysis. He reported stress drop of the M_w 5.8 Pawnee and other Oklahoma mainshocks ranges between 14 and 22 MPa; aftershocks and smaller magnitude earthquakes have lower stress drops, ranging between 1 to 11 MPa, which are typical for the potentially induced and natural earthquakes in the south-central United States.

Kolawole *et al.* (2017) investigated the coseismic liquefaction-induced ground deformations associated with the 2016 Pawnee earthquake event. They reported on one of the first results of a high-resolution near-surface geoelectrical and surface mapping investigation that was designed to image the zones of coseismic liquefaction-induced surface deformation. They show that the locations of coseismic ground deformations in the Pawnee are coincident with areas overlain by Quaternary sediments. They also show that high-resolution geoelectrical imaging can be used as a complementary tool to evaluate areas susceptible to failure during earthquakes to improve hazard mitigation measures.

Pennington and Chen (2017) reported observations of Coulomb stress interactions during the sequence. The three foreshocks promoted failure of the mainshock and early after-

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shocks, and suggested active Coulomb stress interaction between the Sooner Lake fault and the mapped fault during foreshock stage. The mainshock promoted failure for about 70% of the aftershocks, including some events that are not optimally oriented in the regional stress field. Analysis of stress loading on regional faults suggests that the Coulomb stress pattern is consistent with aftershock patterns.

Walter *et al.* (2017) applied matched filter detection to provide a more detailed view of the foreshock activities leading to the mainshock. They reported gradual *b*-value decrease before the mainshock, which suggests gradual differential stress increase before the mainshock.

Barbour *et al.* (2017) used newly uncovered injection data from Osage County, Oklahoma, which shows a significant increase in injection rates leading up to the mainshock. They used a fully coupled poroelastic model of injection into layered subsurface, and they show that Coulomb failure stresses are much stronger when poroelastic stresses are considered. As a consequence of these elevated stressing rates, seismicity rates predicted by a rate-and-state frictional model of the Sooner Lake fault are enhanced, with temporal characteristics in modeled seismicity matching observed seismicity around the source of increased injection rates.

In summary, the 10 different studies provide information about the stress evolution before, during, and after the mainshock, which highlight the importance of coupled poroelastic stresses from injection, dynamic and static stress interactions, and background regional stress field:

Before the mainshock, the coupled poroelastic stress from continued injection activities (peak injection rate occurred in 2012 and 2013) caused the increased seismicity rate in Pawnee County. Within three months before the mainshock, concentrated foreshock activities occurred within the conjugate fault system including the hidden Sooner Lake fault and a previously mapped fault. The foreshock activities reveal gradual differential stress increases with decreasing *b*-value, and also promoted failure of the mainshock through Coulomb stress transfer.

During the mainshock, the coseismic slip of the mainshock is predominately buried in the crystalline basement, with left-lateral slip concentrated to the east and downdip of the hypocenter. Detailed analyses of surface deformation suggest fault zone collapse that is potentially due to enhanced permeability at near-field. The dynamic shaking due to the M 5 mainshocks also caused hydraulic property alternations at far-field. Geoelectrical survey reveals areas with coseismic liquefaction-induced surface deformation, which are coincident with areas overlain by Quaternary sediments.

Following the mainshock, about 70% of the aftershocks within a one-month period received positive Coulomb stress change. The Coulomb stress pattern on regional fault systems is consistent with aftershock distributions.

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