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Induced earthquake and liquefaction hazards in Oklahoma, USA: Constraints from InSAR☆

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ABSTRACT

Oklahoma experienced three earthquakes of M_w5.0 or greater in 2016: the 13-Feb. Fairview earthquake (M_w5.1), the 03-Sep. Pawnee earthquake (M_w5.8), and the 07-Nov. Cushing earthquake (M_w5.0). These events are the first earthquakes in the state exceeding M_w5.0 since the 2011 M_w5.7 Prague earthquake and likely result from wide-scale deep fluid-injection. We use interferometric synthetic aperture radar (InSAR) observations to quantify the magnitude and location of surface deformation associated with these three events, determine the depth ranges of fault slip, and assess the spatial relationship between fault slip and well-calibrated mainshock and aftershock locations. We also include newly reported, calibrated event locations for the Cushing earthquake. We find that the Pawnee earthquake ruptured within the crystalline basement with the shallowest slip occurring at depths of 3.1–4.3 km. We find a similar, though shallower, crystalline basement source for the Cushing earthquake with a minimum depth to slip of 1.6–2.3 km. Despite the smaller magnitude of the Cushing earthquake, it generated anomalously high ground motions and damage compared to the larger Pawnee and Fairview earthquakes. We postulate that the shallow source of the Cushing earthquakes provides one explanation for the higher than expected ground motions. The Fairview earthquake generated no detectable co-seismic displacements, which is consistent with a relatively deep earthquake source (~8.5 km). We do, however, identify a 16 km stretch of floodplain where widespread liquefaction occurred in response to the Fairview earthquake, and where 30 gas production wells were exposed to surface displacements exceeding 5 cm. Consequently, the depth to crystalline basement, which limits the depth of injection-induced earthquakes in Oklahoma, and the potential for liquefaction are important factors in assessing shaking risk in the central United States.

1. Introduction

Oklahoma and surrounding regions have experienced increased earthquake frequency since 2009, a phenomenon that is largely attributed to the practice of wastewater disposal into the Arbuckle formation (e.g., Ellsworth, 2013; Keranen et al., 2013, 2014; Hough and Page, 2015; D.E. McNamara et al., 2015; Walsh and Zoback, 2015; Weingarten et al., 2015; Yeck et al., 2016, 2017). These earthquakes have been interpreted to occur within networks of strike-slip faults located in the crystalline basement and underlying the sedimentary rocks that are exploited for both hydrocarbon withdrawal and wastewater disposal (e.g., Keranen et al., 2013; D.E. McNamara et al., 2015, D. McNamara et al., 2015; Yeck et al., 2016) (Fig. 1). The increased earthquake frequency and resulting damage have led to efforts to reevaluate shaking hazards within the central United States (e.g., Petersen et al., 2014, 2017; Ellsworth et al., 2015). In 2016, Oklahoma experienced three potentially induced earthquakes ≥ M_w5.0, the first such earthquakes since the November 2011 M_w5.7 Prague earthquake: the 13 February 2016 Fairview earthquake (M_w5.1), the 03 September 2016 Pawnee earthquake (M_w5.8, the largest instrumentally recorded earthquake in the state to date), and the 07 November 2016 Cushing earthquake (M_w5.0) (Fig. 1). Both the Pawnee and Cushing earthquakes led to localized damage near the event epicenters (Clayton et al., 2016; Taylor et al., 2017). As with previous earthquakes in Oklahoma, high-quality mainshock and aftershock relocations place these three earthquakes within the crystalline basement (Yeck et al., 2016, 2017). Geodetic studies of the Pawnee earthquake have further corroborated this hypothesis (Fielding et al., 2017; Grandin et al., 2017; Pollitz et al.,

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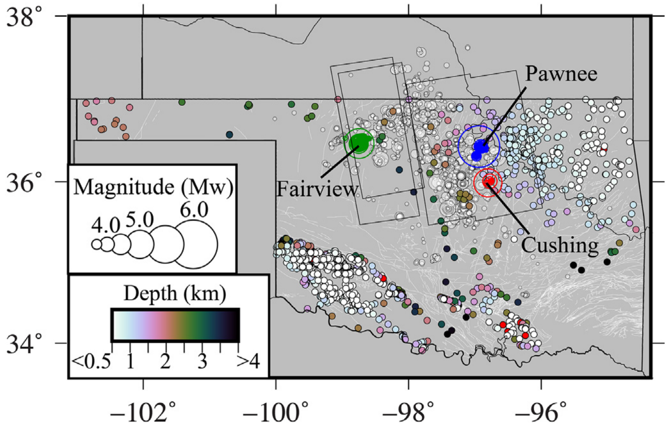

Fig. 1. Location of earthquakes in 2016 in Oklahoma and surrounding regions (white circles) with the February 2016 Fairview, September 2016 Pawnee, and November 2016 Cushing earthquake sequences highlighted. Event locations are from the USGS Comprehensive Catalog, Yeck et al. (2016), Yeck et al. (2017), and this study (Table S2). Broken lines throughout Oklahoma show the locations of mapped crystalline basement faults compiled by the Oklahoma Geological Survey. Depth to basement from well data in Oklahoma is shown in the filled circles. Crystalline basement depths are shallowest in northeast Oklahoma and become progressively deeper in the central and western portions of the state. Basement depths shallow again in southwest Oklahoma where basement in places outcrops. The black polygons delineate the footprints of InSAR observations used in this study.

2017).

In this study, we use remote sensing geodetic observations from interferometric synthetic aperture radar (InSAR) to quantify the surface deformation, or lack thereof, from these three M_w5+ 2016 earthquakes. We use these measurements in concert with calibrated earthquake relocations to estimate the depths of the earthquakes with respect to the crystalline basement and the relocated aftershock sequences themselves (Yeck et al., 2016, 2017). We additionally report a new suite of calibrated earthquake locations for the November 2016 Cushing earthquake. We use this information to assess the geologic settings of these three events, whether they indeed occurred within the crystalline basement, and if their depths within the basement relative to the Earth's surface can explain variations in recorded peak ground accelerations (PGA) and perceived shaking as reported by the U.S. Geological Survey (USGS) Did You Feel It? (DYFI) reports. We additionally examine if spatial gaps within the relocated aftershocks sequences can act as a proper proxy for the location of finite fault slip in scenarios where geodetic observations are not available (Wells and Coppersmith, 1994; Yeck et al., 2016). For the Cushing earthquake, an event that generated anomalously high ground accelerations relative to its moment magnitude, we find that the earthquake likely propagated to the shallowest portion of the crystalline basement (~2 km depth). Shallow rupture explains higher recorded PGA, and this factor combined with the earthquake's proximity to the town of Cushing help explain the infrastructure damage generated by this event compared to the larger Fairview and Pawnee earthquakes. Lastly, we document a region of liquefaction triggered by the Fairview earthquake where active gas

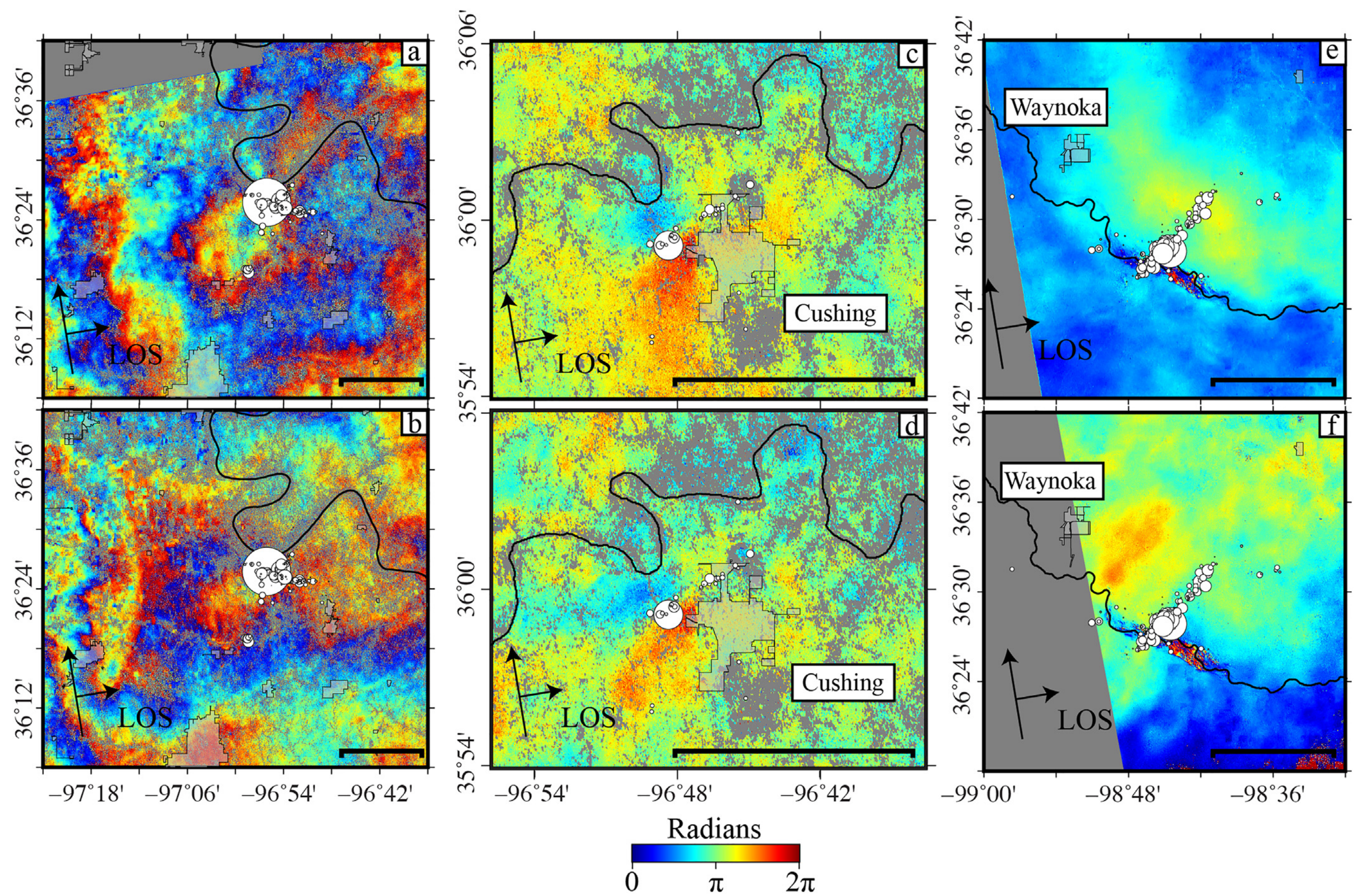

Fig. 2. Single co-seismic, wrapped Sentinel-1 interferograms spanning the (a-b) Pawnee (22 Aug. 2016 to 09 Sep. 2016; 03 Sep. 2016 to 27 Sep. 2016), (c-d) Cushing (09 Oct. 2016 to 14 Nov. 2016; 21 Oct. 2016 to 26 Nov. 2016), and (e-f) Fairview (05 Feb. 2016 to 17 Feb. 2016; 31 Jan. 2016 to 24 Feb. 2016) earthquakes. One phase cycle represents 2.7 cm of displacement in the radar line-of-sight (LOS). Circles indicate the locations of the mainshock and well-located aftershocks reported in this and previous studies (Yeck et al., 2016, 2017). Arrows indicate the satellite pass and LOS directions, respectively. Scale bars are 15 km. The unwrapped interferograms are shown in Fig. S1.