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A Century of Induced Earthquakes in Oklahoma?

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Abstract Seismicity rates have increased sharply since 2009 in the central and eastern United States, with especially high rates of activity in the state of Oklahoma. Growing evidence indicates that many of these events are induced, primarily by injection of wastewater in deep disposal wells. The upsurge in activity has raised two questions: What is the background rate of tectonic earthquakes in Oklahoma? How much has the rate varied throughout historical and early instrumental times? In this article, we show that (1) seismicity rates since 2009 surpass previously observed rates throughout the twentieth century; (2) several lines of evidence suggest that most of the significant earthquakes in Oklahoma during the twentieth century were likely induced by oil production activities, as they exhibit statistically significant temporal and spatial correspondence with disposal wells, and intensity measurements for the 1952 El Reno earthquake and possibly the 1956 Tulsa County earthquake follow the pattern observed in other induced earthquakes; and (3) there is evidence for a low level of tectonic seismicity in southeastern Oklahoma associated with the Ouachita structural belt. The 22 October 1882 Choctaw Nation earthquake, for which we estimate M_w 4.8, occurred in this zone.

Online Material: A discussion of historical earthquakes and populations in Oklahoma, figures of intensity and earthquake location maps and a cumulative count of earthquakes in Oklahoma, and tables of accounts and felt reports.

Introduction

Seismicity rates in the central and eastern United States (CEUS) are generally low, consistent with expectations given the low intraplate strain rate (e.g., Calais *et al.*, 2006; Hough and Page, 2011). Historical seismicity has not been evenly distributed throughout the region, but rather has clustered in a number of identifiable zones. It has remained a matter of debate why seismic strain release is concentrated in certain regions when increasingly precise Global Positioning System results show, at most, very low localized strain levels (e.g., 10^{-9}/yr) (e.g., Calais *et al.*, 2006; Galgana and Hamburger, 2011; Frankel *et al.*, 2012). A growing body of evidence suggests that strain release is clustered, with long periods of dormancy punctuated by periods of heightened activity (e.g., Crone *et al.*, 2003; Clark *et al.*, 2012). Within Oklahoma, the Meers fault, the only fault with documented Quaternary surface rupture, reveals evidence of two earthquakes of M_w 6.5–7 within the past 3400 yr, yet modern seismicity rates associated with this fault have been extremely low (Kelson and Swan, 1990). If previously active zones are now characterized by very low seismicity rates, it follows that infrequent large earthquakes can occur in regions where rates have been low during historical times.

Given evidence suggesting that intraplate earthquakes tend to be temporally clustered (Kelson and Swan, 1990; Crone *et al.*, 2003), it is within the realm of possibility that the recent upsurge of activity in the CEUS could be a naturally occurring cluster. Although this conclusion is not supported by detailed analyses of event sequences (e.g., Keranen *et al.*, 2013, 2014; Llenos and Michael, 2013), it does raise the question of prior activity levels during the twentieth century as well as in historical times. Some past studies have shown that recent seismicity rates are far greater than rates since 1975 (e.g., Ellsworth, 2013) but have not considered the historical and early instrumental catalog. Holland *et al.* (2013) consider the historical catalog back to 1882, using a statistical approach to assess catalog completeness. In this study, we first undertake a review of archival sources to reconsider the historical and early instrumental catalog and consider catalog completeness using an approach based on demographics. We then consider extant records of oil production activities, primarily wastewater injection, to explore whether there is an association between these activities and documented seismicity. Previous studies have suggested that a number of individual events in Oklahoma, as well as Texas, were possibly or probably induced by human activity (Nicholson and Wesson, 1990, 1992; Frohlich and Davis, 2002). The issue has not, however, been considered systematically, and induced earthquakes are assumed to not contribute

Table 1
Historical Earthquakes in Oklahoma with Updated Magnitudes and/or Locations

Date (yyyy/mm/dd)	Local Time (hh:mm)	Latitude (°)	Longitude (°)	M_w*	Account	References†
1882/10/22	04:19	34.70	95.29	4.8	Felt to ≈500 km; toppled chimneys in Choctaw Nation (now Oklahoma); see Ⓔ electronic supplement	1
1897/12/02	00:55	37.09	97.775	4.3	Locally damaging, felt to ≈150–200 km; see Ⓔ Table S2	1
1898/03/02	—	34.933	95.766	3.0	Slight shock felt at south McAlester on Wednesday	2
1900/12/15	07:30	35.800	97.677	3.0	Distinct shock felt at Cashion, 20 miles northwest of Guthrie; huge shivering motion preceded by a low rumbling noise similar to the falling of a round hollow article of large dimensions; people awakened, no damage; apparently not felt at Guthrie	3
1908/07/20	Early	35.671	97.752	3.0	Earthquake vibrations continuing several sections felt in Piedmont, midway between Ft. Reno and Guthrie; apparently not felt in Ft. Reno or Guthrie	4
1914/04/10	17:55	35.026	99.091	3.8	Buildings rocked, dishes thrown from shelves, chimneys toppled at Hobart and surrounding country; apparently not felt in Oklahoma City (distance ≈130 km)	5
1929/12/27‡	18:45	35.500	98.000	4.0	People ran out of houses at El Reno, Union City, and Oklahoma City; felt to ≈100 km	1, 6, and 7
1952/04/09	10:31	35.525	97.850	5.7	See Ⓔ electronic supplement	8

*Magnitude estimates are based on qualitative assessment of macroseismic data, as described in the text and Ⓔ electronic supplement.

†References: 1, Electric Power Research Institute *et al.* (2012); 2, Territorial gossip, *Daily Oklahoman* (Oklahoma City, Oklahoma), 5 March 1898, p. 5; 3, Earthquake in Oklahoma, *Dallas Morning News* (Dallas, Texas), 15 December 1900, p. 5; 4, Earthquake in Oklahoma, *Los Angeles Times* (Los Angeles, California), 20 July 1908, p. I13; 5, Earthquake in Oklahoma, *Tulsa Daily World* (Tulsa, Oklahoma), 10 April 1914, p. 1; 6, Earth tremors at Oklahoma City, *Morning Star* (Rockville, Illinois), 28 December 1929, p. 3; 7, National Oceanic and Atmospheric Administration (NOAA) intensity database (see Data and Resources); 8, Gordon (1988).

‡The 27 December 1929 event is included in the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) catalog (see Data and Resources) with a magnitude estimate of M_w 3.7.

significantly to twentieth-century seismicity rates (e.g., Frohlich and Davis, 2002; Petersen *et al.*, 2014).

Historical and Early Instrumental Earthquake Rates

We examine online archives of historical newspapers to identify additional events and improve magnitudes and locations in the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) catalog (Electric Power Research Institute *et al.*, 2012). Ⓔ Details are provided in the electronic supplement to this article. The analysis identifies several previously unknown small earthquakes and leads to a refinement of magnitudes and/or locations for several previously known events (Table 1). Of note, based on a detailed account of a moderate earthquake on 22 October 1882, we conclude that this event occurred within the then Choctaw Nation in southeastern Oklahoma, about 150 km south of the generally accepted location (Frohlich and Davis, 2002), with a magnitude of approximately M_w 4.8. This part of Oklahoma is within the Ouachita structural belt, which is commonly considered to be an extension of the Appalachian orogen (Keller and Cebull, 1973).

It is difficult to assess rigorously the completeness of an early catalog. Although it is possible that felt earthquakes went unreported during historical times, newspaper articles describing events in 1900, 1908, and 1914 all had the headline, "Earthquake in Oklahoma," suggesting that felt earthquakes were considered unusual and newsworthy. Given the evenness of the population density from 1910 onward (Fig. 1; see Ⓔ also the electronic supplement), we conclude that the catalog should be nearly complete at M_w 4 and close to complete at M_w 3.5. Petersen *et al.* (2014) reached a similar conclusion using a conventional statistical approach to assess catalog completeness from 1925 onward. We thus conclude that the differences in rates reported here between 1900 and 1980, including the relatively high level of activity in the 1950s (Fig. 1), are real. We further conclude that rates were low between 1900 and 1950, with a suggestion of a modest increase of activity during the 1920s and 1930s.

Oil Exploration

Oil exploration in the present-day state of Oklahoma began at the end of the nineteenth century (Franks, 2001; Boyd, 2002). Natural seeps were observed as early as 1830 (Franks, 2001); the first commercially viable well was drilled in 1896 in northern Oklahoma. The first drilling boom commenced shortly after statehood in 1907 (Fig. 2).

Oil exploration fell after oil prices dropped at the start of the Great Depression, although production continued through the 1930s. An increased demand for petroleum during World War II led to new exploration (Franks, 2001). The number of new wells drilled was close to the number during the earlier boom (Boyd, 2002); however, by the 1950s fields were being depleted faster than new fields were being discovered. Enhanced oil recovery (EOR) projects in older

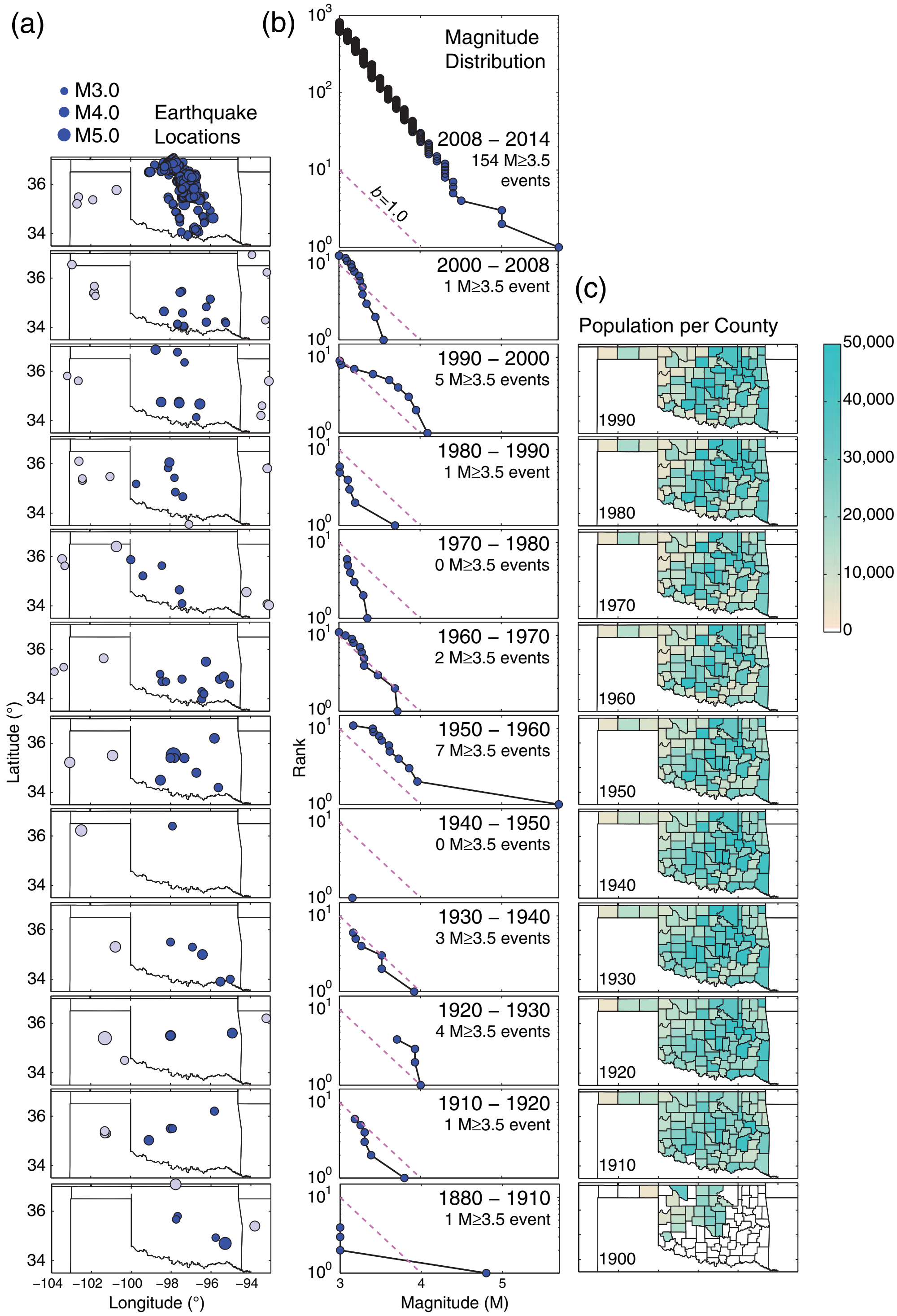

Figure 1. (left) Earthquake locations (blue circles) and (center) magnitudes plotted cumulatively through 2008 are from the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) catalog (see Data and Resources) with modifications and additions from Table 1; post-2008 events are from the Advanced National Seismic System (ANSS) catalog (see Data and Resources). Gray circles in the left column indicate earthquakes in neighboring states. (right) County populations from the U.S. census show that, starting in 1910, Oklahoma had a sizable, well-distributed population, which suggests that earthquakes with $M_w \geq 4$ should be nearly complete. Note that the population color scale saturates at 50,000.

producing fields were undertaken as early as the 1930s (Cloud, 1937). EOR operations, which involve injection of water or steam to increase pressure and enhance recovery of oil, result in large volumes of coproduced wastewater. Moreover, wastewater volumes have increased sharply since 2000 (Keranen *et al.*, 2014; Murray and Holland, 2014;

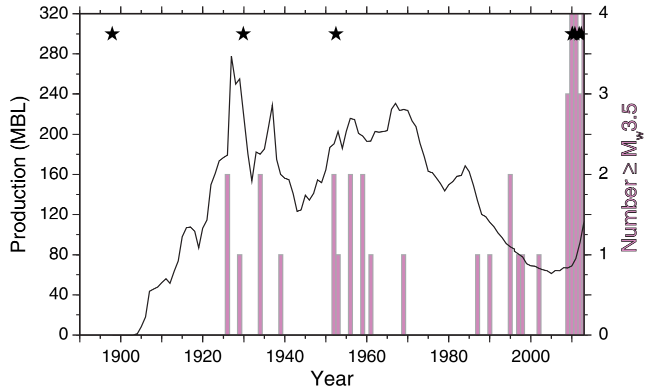

Figure 2. Oklahoma seismicity rates compared with oil production (millions of barrels [MBL]; black line). The bars indicate number of earthquakes of M_w 3.5 or larger in a given year. The black stars denote dates of $M_w \geq 4$ events. Between 2009 and 2014, a total of 26 $M_w \geq 4$ events occurred in the state; for example, over 100 $M_w \geq 3.5$ events occurred in 2014 alone. Note that monthly statewide wastewater volume has increased by a factor of ≈2 since 1997 (Walsh and Zoback, 2015).

Walsh and Zoback, 2015). Widespread use of injection wells for disposal of wastewater generated during oil production began in the 1930s. By state statute, permits were required by the mid-1930s to drill either disposal or EOR wells in the state of Oklahoma, although injection volumes were not regulated. Permit records for each county are available online and document wastewater wells permitted as early as 1945 and EOR wells as early as 1932. State records identify the section, range, and townships for all permits, allowing individual well locations to be pinpointed to within approximately 1.6 km. Range and township information provides locations of wells to within 0.1°.

Evidence for Induced Earthquakes

Seismicity Rates Versus Oil Booms

Identification of injection-induced earthquakes since 2009 has generally been based on a detailed consideration of event hypocenters relative to the locations of injection wells and injection rates or volumes (e.g., Frolich *et al.*, 2014; Keranen *et al.*, 2014; Weingarten *et al.*, 2015). Comparable data are not available for earthquakes before 2009. We therefore compare proxies such as rates of oil and gas production (Boyd, 2002) since 1900 with seismicity rates (Fig. 2), understanding that these proxies do not reflect directly the data we expect to be of prime concern (injection rates and volumes). Notably, two earlier periods of elevated seismicity coincide with the oil booms between 1920–1940 and 1950–1970. Although total production was lower during the 1980s and 1990s, this period coincided with a third major boom in EOR operations (Boyd, 2002). Further, all $M_w \geq 4$ events except the 1897 earthquake occurred either during one of the booms or since 2009. The correspondence between seismicity rates and oil production is consistent with the proposal that $M_w \geq 4$ earthquakes tend to occur during high rates of oil production in the 1920s and 1950s. For smaller earthquakes, a correlation with production is suggested as well. Given the limited duration of the time series and the lack of injection data, the observed correlation is suggestive but not conclusive. In the following sections, we present further analysis that bears on the question of whether or not twentieth-century earthquakes were induced.

The 1952 El Reno Earthquake and Activity during the 1950s

The widely felt earthquake on 9 April 1952 was the largest earthquake in Oklahoma during the twentieth century (Ⓔ Fig. S3a). It is commonly known as the El Reno earthquake because two smaller aftershocks were felt in El Reno, and the most severe damage occurred in El Reno and Oklahoma City in Canadian County (Ⓔ Fig. S3a). Its location, however, is only reported to within 0.1 decimal degrees in the CEUS-SSC catalog, indicating an uncertainty of at least ±10 km.

Two disposal wells were permitted in Canadian County, in 1945 and 1946, reaching depths of 5000 and 8000 ft (Ⓔ Fig. S4). Again, neither injection rates nor volumes are available. A causal relationship between wastewater disposal and the earthquake is suggested, given the proximity of the epicenter to the wells. These were the only two wastewater wells permitted in the vicinity of Oklahoma City as of 1952, and both wells were reported plugged on 8 May 1952, a month nearly to the day after the earthquake occurred. (The operator of the wells, the West Edmond Salt Water Disposal Association, is no longer in business.) One might conjecture that the wells were plugged due to damage from the earthquake itself. We doubt this possibility, however, because a search of articles published in the *Daily Oklahoman* and *Tulsa Daily World* newspapers revealed no mention of documented damage to wells.

A total of seven independent earthquakes occurred in Oklahoma in the 1950s (Fig. 3). The locations of these earthquakes are quite uncertain. Not only are they reported to the nearest 0.1° in the CEUS-SSC catalog, but various studies can give very different locations. For example, Gordon (1988) relocates the 1959 event; their location is more than 30 km from the CEUS-SSC catalog epicenter. We note that the compilers of the CEUS-SSC catalog were apparently unaware of Gordon (1988), even though his relocations almost certainly improved catalog locations available prior to 1988. We further note that, for both of the events for which Gordon (1988) determines a location, the events move significantly closer to the nearest well in operation at that time. Considering these large location uncertainties, events located within 35 km of a well could, in fact, be nearly collocated with the well. We find that six of the seven earthquakes are located within 35 km of a previously permitted wastewater disposal well (Fig. 3). We perform Monte Carlo tests to determine the statistical significance of this correspondence. In these tests, we place seven synthetic earthquakes randomly

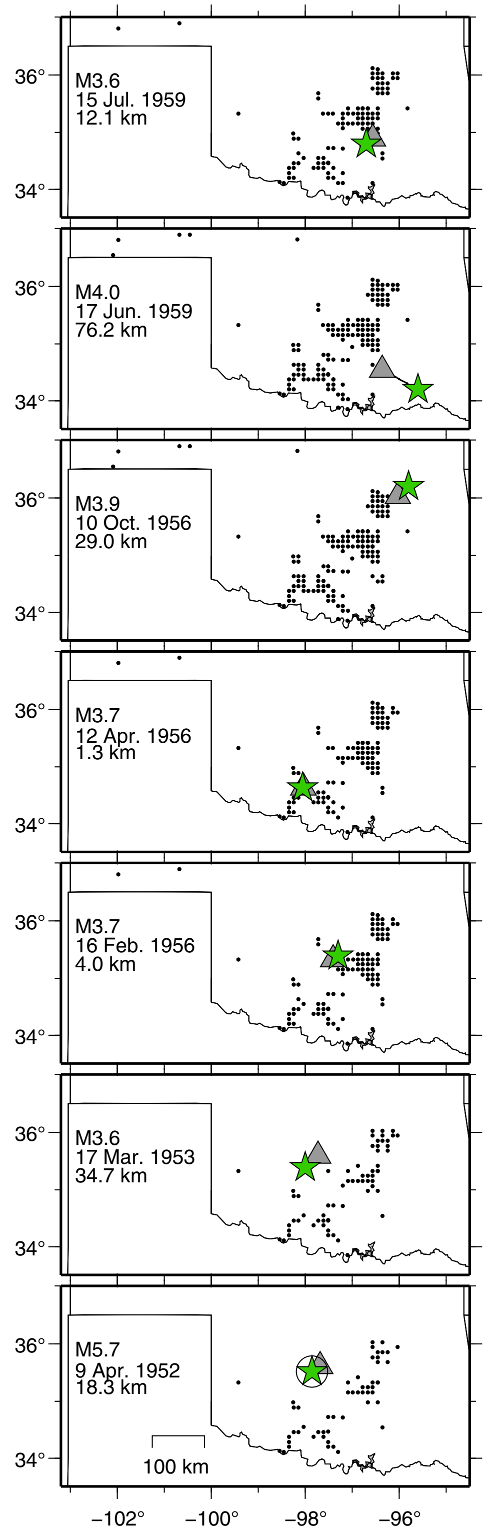

Figure 3. Earthquake locations in the 1950s show good correspondence with wastewater disposal wells. Black dots show township and range locations for all permitted wells prior to the occurrence of the seven independent events (green stars). Note that the earthquake locations have considerable uncertainty (see text); township and range information provides locations of wells to within 0.1°. Six of the seven earthquake locations are within 35 km of a well that received its permit prior to their occurrence (gray triangles); this is statistically significant at $>99\%$ confidence.

within Oklahoma borders and calculate the distance to the nearest well location, using the well locations permitted prior to each of the seven actual earthquakes. We find that six of the seven synthetic earthquakes are within 35 km of a well in only 0.8% of 10,000 Monte Carlo runs. We cannot be certain that the permit records are entirely complete; although record-keeping appears to have been very conscientious, it is possible that some wells were not permitted and/or some records were lost. It is implausible, however, that the possibility of undocumented wells would change the strong statistical correlation. We thus conclude that the spatial correspondence between well locations and prior-permitted injection wells is statistically significant at $>99\%$ confidence. The only event not plausibly associated with a nearby well is the 17 June 1959 M_w 4.0 earthquake in southeastern Oklahoma, within the Ouachita structural belt.

There is also a good temporal correspondence between earthquake locations and nearby wells, as shown in Figure 4. Earthquakes in both the 1950s and the 1980–1990s tend to occur within six months of a nearby well permit date. Although it is not known how much time elapsed between the permit date and the completion of the well, at least since the mid-1990s, the time lag is typically on the order of three months, with about 90% of all wells completed within six months (M. Weingarten, written comm., 2015; also see Weingarten *et al.*, 2015).

Macroseismic Observations

Recent studies (Hough, 2014, 2015) concluded that recent induced earthquakes in the CEUS generate a different pattern of shaking intensities than do tectonic earthquakes, with intensities close to levels expected from regional intensity prediction equations within ≈10 km epicentral distance and lower intensities at greater distance. High near-field intensities may be a consequence of the shallow depths of injection-induced earthquakes. Low intensities at regional distances are consistent with low stress drops (Hanks and Johnston, 1992; Hough, 2014). Here we consider the 9 April 1952 earthquake, for which a relatively large intensity dataset is available. We can compare the intensity distribution with intensities from a recent moderate earthquake in Oklahoma.

For recent moderate earthquakes, spatially rich intensity data are available from the "Did You Feel It?" (DYFI) system (Wald *et al.*, 1999). Some care is required, however, in comparing DYFI data with traditional intensity data determined from postcard questionnaires or archival accounts. Although traditional intensity data and DYFI data both provide estimates of modified Mercalli intensity (MMI), traditional intensity assignments are generally controlled by the most dramatic reported effects, whereas, by definition, DYFI intensities generally represent the average within a given spatial footprint (Hough, 2013). To make the two intensity datasets comparable, we winnowed the DYFI data to include only the highest intensity from an individual ZIP code in cities with at

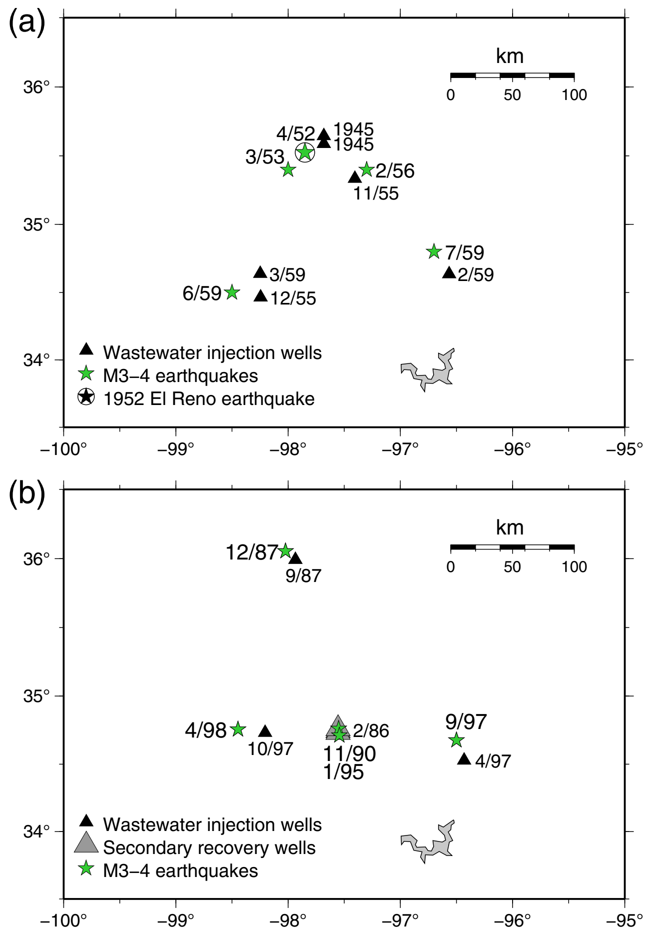

Figure 4. (a) The dates of $M_w \geq 3$ earthquakes in the 1950s show temporal and spatial agreement with nearby injection wells; in particular, most earthquakes occur within 5 months of nearby well permit dates. Note that the earthquake locations have considerable uncertainty (see text). (b) A similar correspondence with both wastewater injection and enhanced oil recovery (EOR) wells is found for $M_w > 3.5$ events in the 1980s and 1990s—nearby wells received permits within 6 months prior to each earthquake.

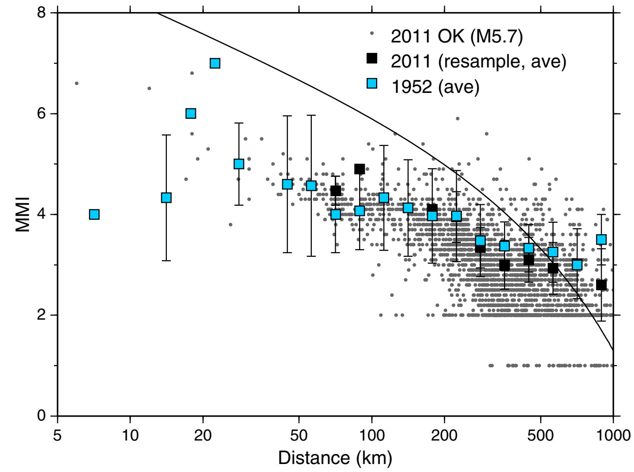

Figure 5. Intensity data for the M_w 5.7 Prague earthquake and 1952 El Reno earthquake. Raw "Did You Feel It?" intensity data for the Prague earthquake (gray dots) are resampled to recreate sampling bias associated with traditional intensities (bin-averaged values shown; black squares). The resampled intensities correspond well to bin-averaged traditional intensity data for the 1952 earthquake. Note that data for distances above 500 km are more sparse and less reliable for both events. The black line shows predicted intensities for an M 5.7 earthquake from a central and eastern United States (CEUS) intensity prediction equation (Bakun and Hopper, 2004).

least three ZIP codes. Hough (2013) shows that this resampling serves to recreate the reporting biases that cause traditional intensities to be higher than representative values in a given spatial footprint (typically a city). Applying this procedure to DYFI data for the M_w 5.7 Prague, Oklahoma, earthquake of 6 November 2011 (Ⓔ Fig. S3b) yields a resampled dataset that is indistinguishable from bin-averaged intensity data for the 1952 event (Fig. 5). We therefore conclude that the 1952 earthquake was roughly the same magnitude as the 6 November 2011 Prague, Oklahoma, earthquake.

Although intensity values within 20 km are sparse for both the El Reno and Prague events, both generated MMI 6.5–7 in the near field, somewhat lower than but closer to the level predicted from the CEUS intensity prediction equation (Bakun and Hopper, 2004), with significantly lower-than-predicted values at distances greater than 20 km. The data for both events thus follow the pattern seen for injection-induced earthquakes (Hough, 2014), providing another line of evidence that the 1952 earthquake was shallow and induced.

Macroseismic data for other twentieth-century events are limited, but we can consider an additional event, the 30 October 1956 earthquake in Tulsa County, with an estimated magnitude of M_w 4.1. This event generated a maximum inferred intensity of MMI 7 near Catoosa, where an oil well was subsequently shut down. Minor damage also occurred in Tulsa. The high near-field intensity for an M_w 4.1 event suggests a shallow depth. The epicenter is within one of the five (of 20) townships and ranges in Tulsa County where secondary recovery operations began prior to 1955. Earlier studies reached similar conclusions regarding both this earthquake and the 1952 earthquake, based on similar (but less detailed) observations and reasoning. Citing only general evidence that the 1952 and 1956 earthquakes were shallow and occurred in proximity to oil wells, Nicholson and Wesson (1990, 1992) suggested that both the 1952 and 1956 earthquakes might have been induced.

Conclusions

Definitive identification of induced earthquakes remains challenging. For historical and early instrumental earthquakes, for which precise locations and depth estimates are unavailable, it is difficult to prove an association of events with oil production activities. However, based on (1) the timing of twentieth-century seismicity, (2) the spatial and temporal correspondence of earthquakes to waste water injection wells in the 1950s and 1980–1990s, and (3) the shaking intensities generated by the 1952 and 1956 events, we conclude that it is possible that earthquakes were induced by oil production activities in Oklahoma as early as the 1920s, and several lines of evidence support our conclusion that much of the earthquake activity in the 1950s and 1980–1990s was induced. We further conclude that the apparent cluster of activity since 2009 is thus not consistent with the level of natural rate fluctuations seen in the past. Indeed, although hazard maps prior to 2009 have shown hazard in central Oklahoma that is somewhat elevated relative to other parts of the central United States (Petersen *et al.*, 2008), we conclude there is only limited incontrovertible evidence of significant tectonic earthquakes in the state. Our analysis does, however, point to a tectonic source zone in southeastern Oklahoma associated with the Ouchita structural belt (Keller and Cebull, 1973). Our results suggest that the rate of tectonic earthquakes in Oklahoma is considerably lower than would be inferred from seismicity rates in the twentieth century and the rate since 2009 far exceeds that during any previous time period since 1900.

Data and Resources

All data used in this report are publically available. The Central and Eastern United States Seismic Source Characterization (CEUS-SSC) catalog and documentation is available at http://www.ceus-ssc.com/ (last accessed October 2015). An online archive of drill permit records is available at http://www.occeweb.com/og/ogowu.html (last accessed February 2015). General information about past earthquakes in Oklahoma is available at http://www.okgeosurvey1.gov/pages/earthquakes/information.php (last accessed February 2015), and http://earthquake.usgs.gov/earthquakes/states/oklahoma/history.php (last accessed February 2015). National Oceanic and Atmospheric Administration (NOAA) intensity data are available at http://www.ngdc.noaa.gov/hazard/intintro.shtml (last accessed February 2015). The Advanced National Seismic System (ANSS) earthquake catalog is available at http://www.quake.geo.berkeley.edu/anss/catalog-search.html (last accessed October 2015).

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