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Natural and Induced Seismicity in the Texas and Oklahoma Panhandles

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ABSTRACT

This article evaluates the probable causes of seismicity in the Texas and Oklahoma Panhandle region, including reviewing historical earthquakes with magnitudes of 3.9–5.4 reported between 1917 and 1980 and more recent earthquakes recorded by stations in the EarthScope Transportable Array (TA) between 2008 and 2011. We believe this is the first scientific publication focusing primarily on Panhandle earthquake activity since a 1939 technical report describing the M_N 5.0 Panhandle earthquake of 1936. Historical earthquakes in 1936, 1966, 1974 and 1980 occurred within or at the boundary of highly productive petroleum fields, and may have been induced by production; however, this conclusion is highly ambiguous because the locations are poorly determined, information about focal depths is absent, and we have only limited information about the petroleum production. We evaluated EarthScope TA data using routine network processing and augmented those detection methods with waveform template matching to identify 374 earthquakes. Most of the detected earthquakes occurred in an east–west band extending across the Texas Panhandle between 35.25° and 36.25° N, coinciding approximately with fault systems associated with the Amarillo-Wichita uplift. Analysis of these data suggests that there are naturally occurring earthquakes in the Texas and Oklahoma Panhandles as well as a few examples of earthquakes possibly induced by production, by wastewater injection, or by hydraulic fracturing. In selected areas, future seismic deployments with station separations of a few kilometers could determine accurate focal depths for Panhandle earthquakes, making it possible to better assess whether observed events were natural or induced.

Electronic Supplement: Analysis of Transportable Array data recorded in 2008–2011, figures showing data used for determining the distance correction for Panhandle local magnitude, felt areas, detail of the Oklahoma Panhandle region, and tables of earthquakes mapped, the seismic-velocity model used for relocation in this study, and the earthquake locations determined in this study.

INTRODUCTION

Since about 2008, the rate of earthquake activity has increased in the central United States (Ellsworth, 2013); most scientists agree that this is due to earthquakes induced by wastewater injection disposal in Oklahoma and to a lesser extent in Texas (Frohlich *et al.*, 2016). However, this increase in activity has not been observed in the so-called Panhandle regions of these states, the approximately square northernmost region of central Texas bounded by latitudes 34°–36.5° N, 100°–103° W, and, situated just to the north, the rectangular western panhandle part of Oklahoma extending from 36.5° to 37° N. Rather, these recent induced earthquakes have occurred in central and northern Oklahoma (Keranen *et al.*, 2013, 2014; Walsh and Zoback, 2015; Weingarten *et al.*, 2015), northeast and east Texas (Frohlich *et al.*, 2011, 2014, 2016; Justinic *et al.*, 2013; Hornbach *et al.*, 2015; Walter *et al.*, 2016; Scales *et al.*, 2017), and along the Gulf Coast of Texas (Frohlich *et al.*, 2012; Frohlich and Brunt, 2013).

The present article focuses on the seismicity of the Texas and Oklahoma Panhandles, evaluating both historical and recent seismicity and speculating on possible relationships with activities associated with petroleum production. The Panhandle region merits attention for four reasons. First, it is seismically active (see Fig. 1 and Table 1); over the last century, there have been three earthquakes having local magnitude M_L, short-period body-wave magnitude m_b, or felt-area magnitude M_N of 5 or greater (in 1925, 1936, and 1948) and four more with M_N exceeding 4 (in 1951, 1966, 1974, and 1980). Second, the Panhandle region has a long history of petroleum production beginning before 1920; this is approximately the time of the earliest reports of Panhandle earthquakes (Frohlich and Davis, 2002), and epicenters for many of the larger subsequently reported earthquakes are situated within or on the boundary of active oil and gas fields (e.g., see Figs. 1 and 2, and Ⓔ Figs. S3, S4, and S7, available in the electronic supplement to this article). Third, seismograph station coverage in and near the Panhandle was sparse prior to the temporary deployment of the EarthScope Transportable Array (TA) stations in 2008–2011 and, more recently, permanent stations deployed in 2016–2017 as part of the state-funded TexNet network (Frohlich *et al.*, 2016). Earthscope TA data have been searched systematically to identify and locate small-magnitude earthquakes elsewhere in Texas (Frohlich, 2012; Frohlich and Brunt, 2013; Walter *et al.*, 2016) but not in the Panhandle. Finally, the most recent published investigation

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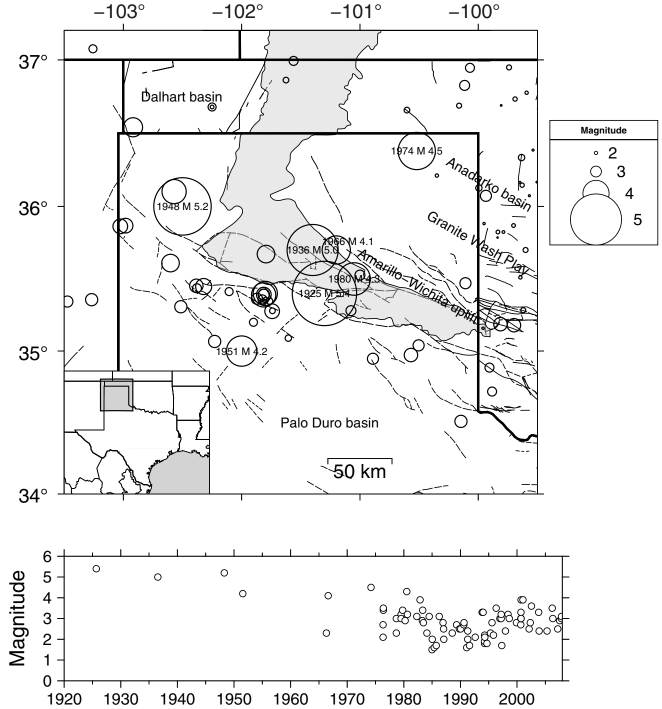
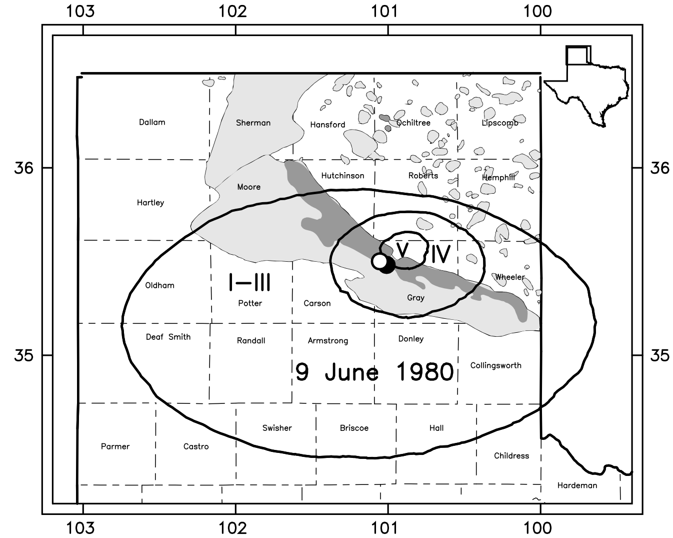


▲ **Figure 1.** Seismotectonic features of the Texas and Oklahoma Panhandle regions. Circles are earthquakes in the historical catalog for this region (Ⓔ Table S1, available in the electronic supplement to this article). Larger circles are historical earthquakes with magnitudes larger than 4 discussed in the Historical Panhandle Earthquakes section; labels indicate the year of occurrence. Thinner lines are faults from Ewing (1990) in Texas and from Marsh and Holland (2016) in Oklahoma. Light gray shaded feature is the Panhandle-Hugoton gas field (digitized from Sorenson, 2005).

we have found concentrating primarily on a Panhandle earthquake or earthquakes is the Sellards (1939) study of the 30 June 1936 earthquake. Thus, the intent of the present study, 80 yrs later, is to provide a long-overdue update on the subject of Panhandle seismicity.

Following this introduction, we discuss the geology and historical seismicity of the Panhandle region prior to 2008 when



▲ **Figure 2.** Felt area for the 9 June 1980 M_N 4.3 Pampa earthquake. The white circle is the location from the International Seismological Centre; the black circle is the location of Gordon (1988). Areas labeled with roman numerals indicate areas reporting modified Mercalli intensities (MMIs); smaller labels are county names. Shaded regions indicate major oil (dark shading) or gas (light shading) fields established prior to 1980, as mapped by Galloway *et al.* (1983) and Kosters *et al.* (1989). Map and isoseismal information are redrawn from Frohlich and Davis (2002). As with several other of the larger Panhandle earthquakes, the highest-intensity region is within or near the boundary of a major petroleum field, the Panhandle-Hugoton field.

Earthscope TA station deployment began. Then, we describe the methods and results of our analysis of the EarthScope TA data recorded between 2008 and 2011 in the Panhandle. We apply a network matched-filter technique, augmented by analyst review, to identify and locate small-magnitude earthquakes occurring between 2008 and 2011 and a few events from 2012–2016 (when installation of the state-funded TexNet network began). The events identified include numerous earthquakes not previously identified through the U.S. Geological Survey (USGS)

Table 1
Historical Panhandle Earthquakes Discussed in Detail in This Article

Date and Time (yyyy/mm/dd hh:mm)	Latitude (°)	Longitude (°)	Magnitude	Citation
1917/03/28 19:56	35.4	−101.300	3.9 M_N	F&D (Woollard, 1968)
1925/07/30 12:17	35.4	−101.300	5.4 M_N	F&D (Docekal, 1970)
1936/06/20 03:24	35.7	−101.400	5.0 M_N	F&D (Docekal, 1970)
1948/03/12 04:29	36	−102.5	5.2 M_N	F&D (Reagor *et al.*, 1982)
1951/06/20 18:37	35	−102	4.2 M_N	F&D (Docekal, 1970)
1966/07/20 09:04	35.7	−101.2	4.1 M_N	F&D (von Hake and Cloud, 1968)
1974/02/15 13:33	36.384	−100.525	4.5 m_b	F&D (ISC)
1980/06/09 22:37	35.503	−101.054	4.3 M_N	F&D (ISC)

For magnitudes M_N, magnitude determined from felt area; for source of epicenter, F&D, Frohlich and Davis (2002); ISC, International Seismological Centre.

routine monitoring. Finally, we summarize our conclusions concerning the relationship between seismicity and activities associated with petroleum production for both recent and historical earthquakes.

PANHANDLE GEOLOGY AND HISTORICAL PETROLEUM PRODUCTION

The most prominent feature of the Texas Panhandle is the southeast-to-northwest-trending Amarillo-Wichita uplift that extends well into central Oklahoma (Fig. 1). The shedding of sediments from this uplift and subsequent deposition in an adjacent rift led to the formation of the Anadarko basin to the northeast and the Palo Duro basin to the southwest. The Anadarko basin consists of much thicker sediment packages than the Palo Duro basin. Thus, the Texas Panhandle can be described very broadly as a belt of Precambrian rocks subcropping or uplifting sedimentary strata that form hydrocarbon traps (Sorenson, 2005). In the Ordovician, sedimentary deposition across a broad area formed the Ellenburger and Arbuckle units in Texas and Oklahoma, respectively. The subsequent erosion of exposed granites in the Paleozoic Amarillo-Wichita Mountains (Ewing, 1990) formed a vast series of fans and deltas overlying the Ordovician sediments. These formations that are now sandstones and conglomerates with interbedded shales compose the Granite Wash. By the early Permian and late Carboniferous period, the Amarillo-Wichita Mountains and Granite Wash were covered by deposition of carbonates and later by thick sequences of evaporites.

The Panhandle oil and gas field was discovered with a successful well in 1918 drilled in Potter County at a dome mapped earlier by Charles N. Gould, the first Director of the Oklahoma Geological Survey (OGS; Pippin, 1970; Barlett, 1982; Smith, 2017). Deep marine shales likely produced the hydrocarbons that migrated through the Granite Wash to the trap formed by Permian evaporites. Subsequent efforts produced oil from discoveries in Carson County (1921), Hutchison County (1923), Wheeler County (1925), Gray County (1925), and Moore County (1927); peak annual production in 1927 exceeded 40 million barrels. Later exploration in the Oklahoma Panhandle and southwest Kansas suggested a wide region was structurally connected, and in its entirety, this is now known as the Panhandle-Hugoton field (Fig. 1) that extends as far north as west-central Kansas.

Early efforts in the Panhandle Field focused on oil production; however, gas reserves were considerably more substantial. and the gas reservoir that flanks the areas of oil production is now considered the largest gas play in the United States. There were insufficient markets for the gas because of the remoteness of the field (Smith, 2017), prompting in 1933 the passage by the Texas legislature of the Sour Gas Law that allowed operators to strip the gas of its natural gasoline and blow the residual gas into the atmosphere. Until the law was repealed in 1935, over a billion cubic feet of gas per day was flared.

Although much of the early exploration of the Texas Panhandle focused on the central portion, during the last decade there has been considerable production in the Granite Wash play in the northeast Texas Panhandle. This economic shift eastward is in part driven by engineering advances in horizontal drilling and hydraulic fracturing that make what were considered unconventional plays economically feasible. During production, wastewater is either produced as flowback from the hydraulic fracture or coproduced from the formation and reinjected deep underground, presumably into the Arbuckle group that directly overlies crystalline Precambrian basement rocks.

The faults that make up the root of the Amarillo-Wichita uplift and trend east-southeast may have existed since Precambrian times. Structural interpretations of geophysical datasets suggest that the fault bounding the uplift's northern margin has undergone reverse-faulting motion in the past. However, based on the analysis of exposed uplifted granites, Goldstein and McGookey (1982) deduce a northwest-trending maximum compression and southwest-trending least-compressive stress, though the current sense of motion on these faults is likely normal. There are three focal mechanisms available for Panhandle earthquakes (Herrmann, 1979; Herrmann *et al.*, 2011); these are also consistent with extension along an approximately north–south direction perpendicular to the strike of the Amarillo-Wichita uplift. They are also consistent with nearly east–west $S_{\mathrm{H\,max}}$ directions determined from borehole breakouts and drilling-induced fractures reported by Lund Snee and Zoback (2016).

HISTORICAL PANHANDLE EARTHQUAKES

Several previous authors suggested that Panhandle seismicity may be induced by petroleum activity (Pratt, 1926; Frohlich and Davis, 2002). This is because the highest-intensity regions for several of the larger events coincided with active petroleum fields or their boundaries (see below and Figs. 1 and 2, and Ⓔ Figs. S3, S4, and S7) and also because all known Panhandle earthquakes occurred since petroleum development began in the Panhandle between 1910 and 1920. This is mitigated by the observation that prior to 1910 the population of the Panhandle was very sparse, and felt earthquakes may not have been reported. Nevertheless, there were settlements in Donley, Wheeler, and Oldham Counties prior to 1880, and the *Clarendon News*, the region's first newspaper, was first published in 1878. Thus, the apparent relationship with petroleum development has some credibility.

Generally, the evidence indicates that some Panhandle earthquakes have a natural origin. The highest-intensity region for the 12 March 1948 M_{N} 5.2 Dalhart earthquake was in Dallam and Hartley Counties (see Ⓔ Fig. S5), an area having no vigorous contemporaneous petroleum activity. Although the strongest felt reports for the 28 March 1917 M_{N} 3.9 earthquake were from Carson and Potter Counties (Ⓔ Fig. S2), vigorous production did not begin in these counties until 1921 and 1918, respectively.

The largest historical Panhandle earthquake, the M_{N} 5.4 event of 30 July 1925, was felt most strongly in Hutchison, Carson, and Potter Counties (Ⓔ Fig. S3), including areas within the Panhandle field. Oil exploration and production was accelerating in all these counties by 1925; however, total oil production was still relatively low in comparison with the following decade. For example, Pippin (1970) dates the beginning of the Panhandle boom to April 1925, when a highly productive well was completed in Hutchison County. Thus, it is unlikely, although possible, that the 1925 earthquake was induced.

Elsewhere in the United States, in the 1920s and 1930s where apparently induced earthquakes occurred, typically very large production volumes from very shallow strata (less than two km) had been ongoing for several years prior to earthquake activity. Also, there was evidence that these earthquakes were very shallow, as indicated by the presence of surface cracks and a very abrupt fall-off with distance of the modified Mercalli intensities. Examples include the 1925 Goose Creek and 1932 Wortham-Mexia earthquakes in Texas (Frohlich *et al.*, 2016) and several earthquakes in the Los Angeles basin occurring between 1915 and 1932 (Hough and Page, 2016). Our interpretation is that, prior to the June 1925 Panhandle earthquake, cumulative production volumes in the Panhandle field are too low to make an induced cause plausible.

However, an induced cause is possible for the 30 June 1936 M_N 5.0 earthquake. Like the 1925 event, it was most strongly felt within the Panhandle field (Ⓔ Fig. S4). According to Bartlett (1982), prior to 1938 the Panhandle field had produced more than 300 million barrels of oil and more than 7.5 trillion cubic feet of gas. Such high cumulative volumes make the Panhandle situation in 1936 somewhat similar to that accompanying the 1925 Goose Creek and 1932 Wortham-Mexia earthquakes (Frohlich *et al.*, 2016).

Generally, prior to about 1960 or so, sparse station coverage in the central United States made instrumental locations absent or highly uncertain, and thus the evidence that petroleum activities caused an earthquake is often weak. An example is the 20 June 1951 M_N 4.2 Amarillo earthquake (Ⓔ Fig. S6); the International Seismological Summary's instrumental location was determined using only five P arrivals, with no reporting station closer than 800 km (Frohlich and Davis, 2002). This epicenter and the epicenter determined instrumentally by Gordon (1988) are both situated about 95 km from the epicenter favored by Docekal (1970) that is more consistent with felt reports. In any case, the 1951 earthquake is unlikely to be induced, because we are unaware of vigorous contemporaneous petroleum production near either of the proposed epicentral locations.

In contrast, the instrumentally determined epicenters for the three earthquakes that occurred on 20 July 1966, 15 February 1974, and 9 June 1980 (Fig. 2 and Ⓔ Fig. S7) are likely to be accurate to within at least 20 km. For all three earthquakes, the International Seismological Centre determined locations incorporated phases from more than 20 stations, including two or more at 200–300 km distances. The epicenters for both the 1966 and 1980 earthquakes lie within or on the boundary of heavily produced portions of the Panhandle field. There are also active gas fields in Ochiltree and Lipscomb Counties near the 1974 epicenter. Thus, it is possible that all three earthquakes were induced. Incidentally, Shurbet (1969) suggested that the 1966 earthquake might have been induced by the filling of Lake Meredith (see Ⓔ Fig. S7) that had begun in January 1965 after the completion of the Sanford Dam in Hutchison County. This seems unlikely to us, because the lake, which has a maximum depth of about 30 m, was less than half full when the earthquake occurred; also, most reservoir-induced earthquakes occur under conditions in which maximum water depths are 50 m or more (Gupta, 2002).

Thus, of the Panhandle earthquakes in Table 1, we conclude that it is unlikely that the events of 1917, 1925, 1948, and 1951 were induced by activity associated with petroleum production. The 1936, 1966, 1974, and 1980 earthquakes are possibly induced; however, the evidence is not conclusive because it relies solely on the observation that the earthquakes occurred in or near areas where significant petroleum production had been ongoing for many years. Unlike the Goose Creek and Mexia-Wortham earthquakes described by Frohlich *et al.* (2016) and at least one of the Los Angeles basin earthquakes described by Hough and Page (2016), for the Panhandle earthquakes we are unaware of evidence such as surface cracks or very high intensities near the epicenter that suggest a very shallow depth.

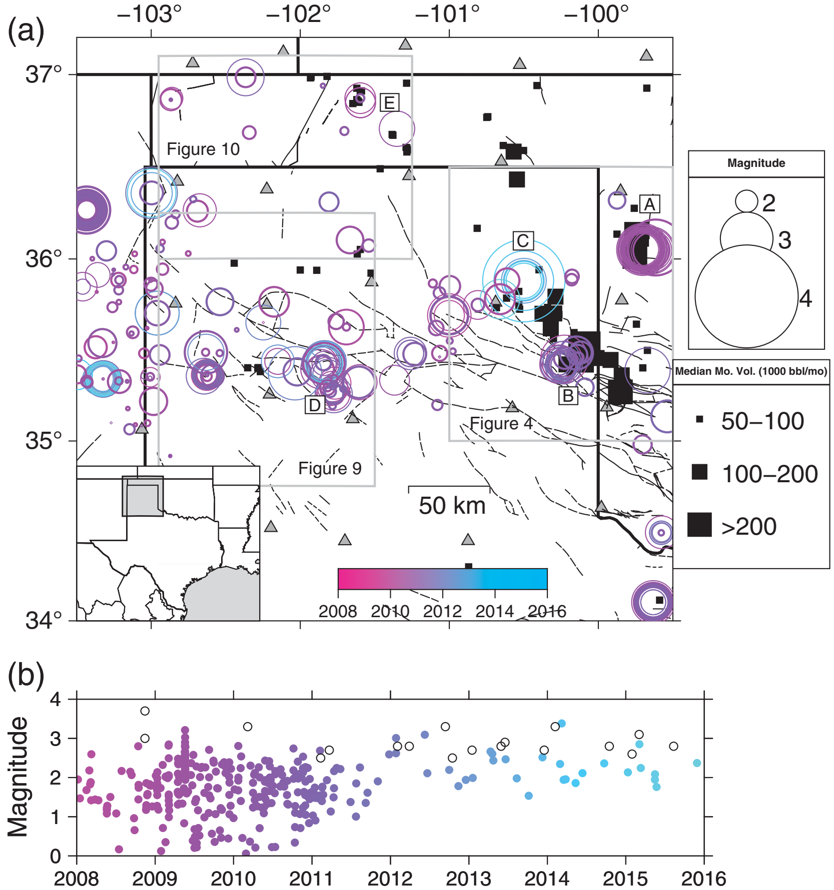
Over the last 50 yrs, as additional permanent seismograph stations were installed in the central United States, increasing numbers of lower-magnitude earthquakes were located in the Texas and Oklahoma Panhandles. In addition, regional stations operated by the OGS contributed to cataloging that activity (Fig. 1 and Ⓔ Table S1).

METHODS: ANALYSIS OF TRANSPORTABLE ARRAY DATA RECORDED IN 2008–2011

In the Ⓔ electronic supplement, we provide a detailed description explaining how we analyzed data recorded by the Earthscope TA to locate earthquakes occurring between May 2008 and March 2011. Similar to recent studies (Walter *et al.*, 2016, 2017), our analysis of TA data to detect and locate earthquakes consisted of four steps: initial processing to identify and locate candidate events by automatic phase detection and event association, manual phase-picking adjustment and relocation to select a group of well-recorded events to be used for template matching, waveform cross correlation with these template events to identify additional events and to pick P and S phases, and relocation of all template and additional events using a double-difference algorithm.

In this study, we identified 110 earthquakes used for template matching (the parent earthquakes in Ⓔ Table S3). The epicenters for most of these events have an absolute accuracy of about 1–2 km, but we could not determine their focal depths accurately. This is because the spacing between stations in the TA network is about 70 km, and thus there is an unresolvable trade-off between focal depth and origin time.

Using waveform matching, we identified an additional 264 events within the study area. Including the 110 template earthquakes, there are altogether 374 earthquakes in the study area (Ⓔ Table S3). The Ⓔ electronic supplement also describes how we determine an adjusted local magnitude M_{Ladj} for these events (see Ⓔ Fig. S1), using methods similar those used in



▲ **Figure 3.** (a) Earthquakes (circles) and wastewater injection wells (filled squares) in the Panhandle region. Earthquakes are as identified from the Transportable Array (TA) earthquake association and matched-filter methodology. TA stations (gray triangles) were operational between 2008 and early 2011. Wastewater-injection well rates are median monthly rates during the TA study period. Faults mapped as in Figure 1. Light gray boxes indicate map areas of subsequent figures; squares labeled with letters "A–E" indicate clusters of earthquakes discussed throughout the text and labeled alphabetically in the order in which they are discussed. (b) Earthquake magnitudes plotted as a function of time, whereas filled circles correspond to epicenters shown in (a). Open black circles indicate earthquakes reported by Advanced National Seismic System–U.S. Geological Survey during this time period. As TA stations began shutting down in early 2011, the number of earthquake detections was reduced, though the matched-filter technique continues to detect some events recorded by the remaining stations.

Walter *et al.* (2016). The procedure was designed so that M_{Ladj} was generally consistent with the magnitudes $m_{\mathrm{b}Lg}$ or M_{wr} assigned by the USGS for events for which $m_{\mathrm{b}Lg}$ or M_{wr} was available.

SEISMICITY 2008–2011: RELATION TO INJECTION AND PRODUCTION

Eastern Texas Panhandle—Western Oklahoma

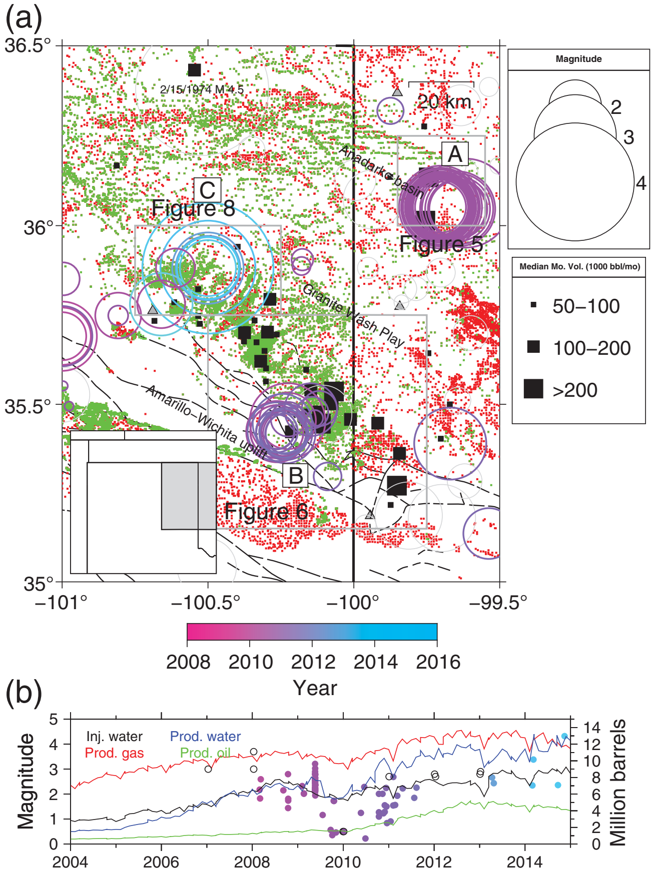
Most Panhandle earthquakes occurring since 2008 occurred within a roughly east–west band extending across the Texas Panhandle and lying between 35.25° and 36.25° N (Fig. 3). Much of this seismicity tends to be associated with Amarillo–Wichita structural features, and this certainly holds in the eastern Panhandle (Fig. 4).

Petroleum production has been very vigorous in the eastern Panhandle region in the twenty-first century (see Ⓔ Fig. S8); there are oil and gas wells covering nearly the entire area mapped in Figure 4, and 76 of the 374 earthquakes identified in this study are situated within the area mapped in Figure 4; of these, 55 are members of three major clusters.

Cluster A (Figs. 4 and 5), with 28 events occurring in 2009 near 36.05° N and 99.7° W, is situated in the Anadarko basin in Oklahoma, near the Oklahoma–Texas border, and is centered within 8–20 km of two high-rate injection wells. This activity followed a major increase in the rate of wastewater injection that began in 2007 and persisted until 2010. Thus, it is plausible these earthquakes were triggered by wastewater injection.

Cluster B (Figs. 4, 6, and 7), situated in Texas near the Oklahoma–Texas border at 35.4° N and 100.24° W, has 19 events occurring between 2008 and 2011 and located within 5 km of a high-rate injection well. Although 11 of these earthquakes did follow shortly after a sharp increase in wastewater injection in 2010, eight others occurred in 2008 and 2009, well prior to this increase. Some seismicity precedes the substantial increase in wastewater injection for the well most proximal to the earthquake clusters; thus, it is possible that some of the later earthquakes were triggered by wastewater injection. Wastewater injection plausibly promoted ongoing seismic activity of natural or tectonic origins.

Cluster C, also situated within Texas (Figs. 4 and 8) has eight events occurring from 2013–2015 near 35.88° N and 100.5° W. There are two low-rate injection wells within 12 km of this cluster and a somewhat higher-rate injection well about 20 km distant. Injection as a cause of triggering seems unlikely, because these distances seem too great, and there are no prior abrupt changes in injection rates. According to FracFocus data, the area near Cluster C has undergone extensive hydrofracturing. We analyzed the spatial and temporal correlation between earthquakes in this cluster and FracNotice hydraulic fracturing operations. We find that some earthquakes occurred within 10 km of, and within ten days following the commencement of, nearby hydrofracture operations (yellow stars in Fig. 8), although there were also numerous hydrofracturing operations within 10 km starting in 2012, well before the seismicity began (white stars in Fig. 8). Evidence that hydrofracturing triggered seismicity is plausible, though relatively weak. The spatial and temporal correlation exists and it remains a possibility that these earthquakes were triggered by hydraulic fracturing.

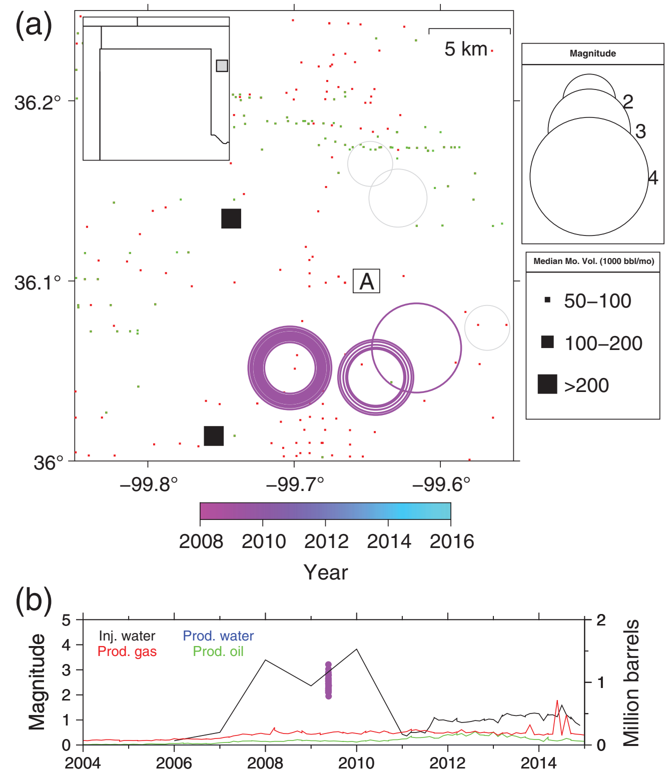


▲ **Figure 4.** (a) Map of the eastern Texas Panhandle region (see Fig. 3), showing earthquakes (circles), wastewater injection wells (filled squares), and production wells (red and green dots). Light gray rectangles indicate map areas for Figures 6, 7, and 9; squares labeled with letters "A–C" indicate clusters of earthquakes discussed in the Eastern Texas Panhandle—Western Oklahoma section. (b) Time series of monthly rates of produced water, produced gas (barrel of oil equivalent [BOE], 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, and injected water for the region mapped in (a). Earthquake magnitudes are plotted with respect to time.

We analyzed the spatial and temporal correlation for all the earthquakes in our study (across both Panhandles), and this is the only seismic cluster that exhibits the spatial and temporal correlation between earthquakes and hydraulic fracturing (within 10 km and ten days).

Western Texas Panhandle

Of the 374 earthquakes identified in this study, 93 occurred in the western Panhandle within the area mapped in Figure 9. Here, there are several clusters of earthquakes (generally labeled cluster D), occurring mostly in 2009 and 2010 and apparently associated with the Amarillo-Wichita uplift. One of these clusters occurs within 5 km of active injection wells and producing oil and gas wells. However, the remaining clusters mostly occur within areas where there are no nearby oil, gas, or injection wells. The available evidence suggests that some earthquakes



▲ **Figure 5.** (a) Detail of the western Oklahoma region (see Fig. 4), showing earthquakes (circles) in cluster "A," wastewater injection wells (filled squares), and production wells (red and green dots). (b) Time series of monthly rates of produced water, produced gas (BOE, 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, and injected water for the region mapped in (a). Earthquake magnitudes are plotted with respect to time.

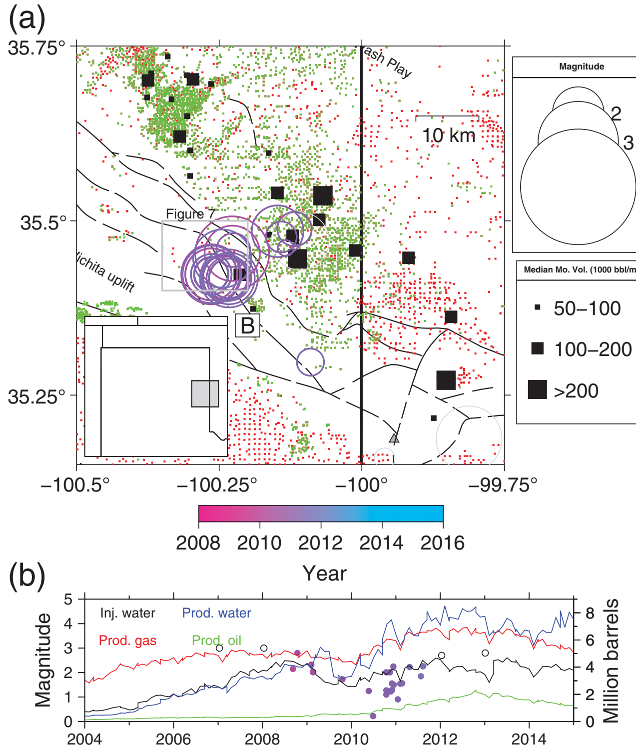
mapped in Figure 9 could be induced, whereas others may have a natural origin.

Oklahoma Panhandle

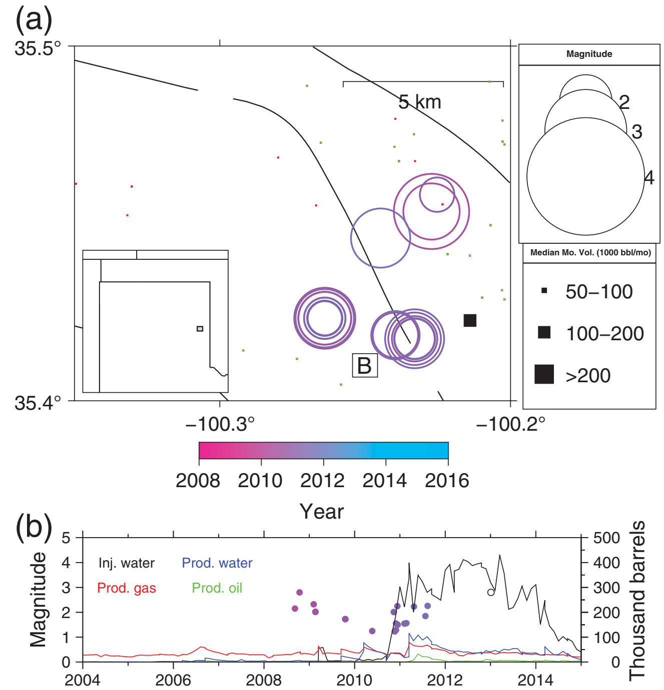
Only 30 of the earthquakes identified in this study occurred within the area mapped in Figure 10. Some of these do occur in areas of active oil production, and a few occur near relatively low-rate injection wells. For example, Ⓔ Figure S9 shows four earthquakes (cluster E) that occur in 2008 within 5 km of three injection wells. They occur following an increased rate of injection (one among several). Thus, it is possible they are triggered by injection, but the evidence is mixed.

DISCUSSION

Our review of historical earthquakes (1917–1980) and analysis of recent earthquake activity (2008–2011) demonstrates that the Texas Panhandle is moderately active seismically. The recent seismicity occurs in a broad zone extending from about 35.25° to 36.25° N across the central Panhandle, coinciding approximately with fault systems associated with the Amarillo-Wichita uplift. The recent activity in the central Panhandle occurs approximately in the same region as historical earthquakes occurring



▲ **Figure 6.** (a) The eastern Texas Panhandle region detail (see Fig. 4), showing earthquakes (circles) in cluster "B," wastewater injection wells (filled squares), and production wells (red and green dots). Light gray rectangle indicates the map area for Figure 7. (b) Time series of monthly rates of produced water, produced gas (BOE, 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, and injected water for the region mapped in (a). Earthquake magnitudes are plotted with respect to time.



▲ **Figure 7.** (a) Detail of the eastern Texas Panhandle region (see Fig. 6), showing earthquakes (circles) in cluster B, wastewater injection wells (filled squares), and production wells (red and green dots). (b) Time series of monthly rates of produced water, produced gas (BOE, 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, and injected water for the region mapped in (a). Earthquake magnitudes are plotted with respect to time.

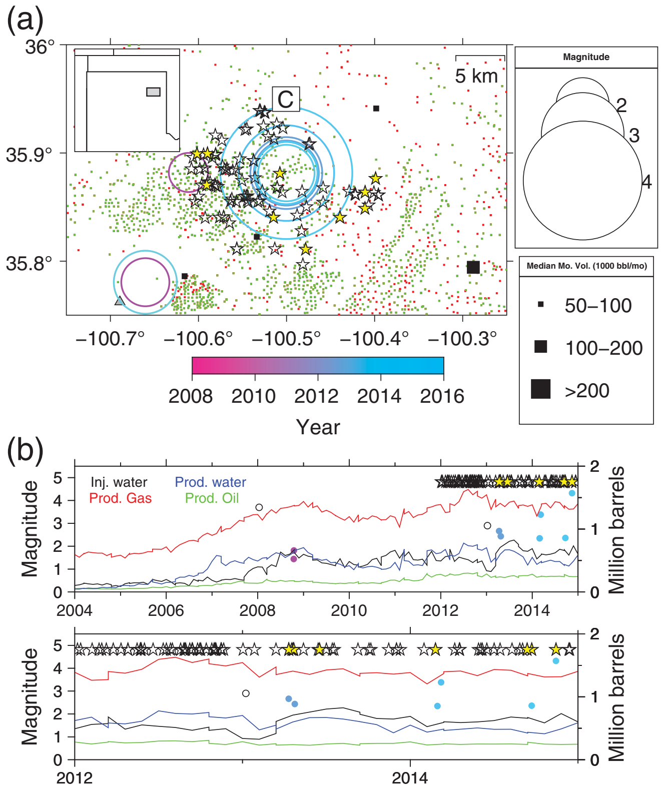
in 1925, 1936, 1966, and 1980. It is possible that some of these historical earthquakes were induced because they occurred within and at the boundary of producing petroleum fields. But overall, the evidence is weak because the depths and locations of these historical earthquakes are poorly known.

There are also recent earthquakes in the western Panhandle in locations generally corresponding to where historical earthquakes occurred in 1948 and 1951, although the epicenters of these early events are poorly known. Most of these earthquakes occurred in areas where there is no ongoing production or wastewater injection and thus they appear to be of natural origin.

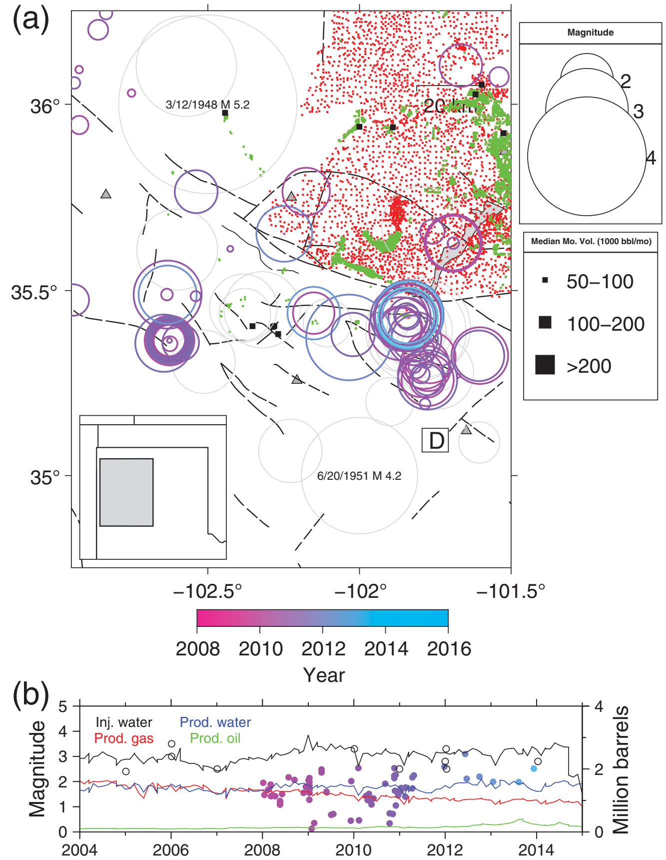
In the eastern Texas Panhandle and western Oklahoma, recent earthquake activity occurs along the Amarillo-Wichita uplift in an area where historical large earthquakes are absent. Here, there is one earthquake cluster in western Oklahoma (cluster A) in which the epicenters occur within 8–20 km of high-rate wastewater disposal wells, and thus it is plausible that these earthquakes are injection induced. We identify other recent earthquake clusters in Texas and Oklahoma for which an injection-induced cause is possible, but the evidence is mixed. Clusters B and E and at least one cluster (cluster C) are spatially and temporally correlated with hydraulic fracturing that may have plausibly triggered these earthquake clusters. There are active oil and gas wells across the entire northeastern Panhandle (Ⓔ Fig. S8), and thus it is possible some regional earthquakes could also be triggered by production, though it is not clear how one would test such a hypothesis.

In summary, the record indicates that some Panhandle earthquakes seem to have a natural tectonic origin, and a few Panhandle earthquakes probably are induced, especially in the eastern Panhandle, but for the remainder there is insufficient evidence available at present to assess whether they are natural or induced. As a broad generalization, our results are similar to a recent study some of the authors of this article conducted utilizing TA data near the Bakken play of North Dakota (Frohlich *et al.*, 2015), where we found some evidence for isolated clusters that could have been induced, but that study revealed a very low seismicity rate and weak evidence for induced activity. In the Panhandles, we find a generally higher seismicity rate with a few weak cases where seismicity may have been induced by wastewater injection and hydraulic fracturing. In addition, we note that there is insufficient information to determine focal depths for any of the earthquakes discussed here; the station spacing for the TA network was 70 km. Thus, it is not possible to accurately assess whether the hypocenters of earthquakes reported near injection wells occurred at or near the depths of injection or to associate them with specific producing strata.

Although our central argument is that, in general, the Panhandles of both states were woefully devoid of modern seismic



▲ **Figure 8.** (a) Detail of the eastern Texas Panhandle region (see Fig. 4), showing earthquakes (circles) in cluster "C," wastewater injection wells (filled squares), and production wells (red and green dots). Stars are locations of hydrofractured wells within 10 km of earthquake epicenters; yellow stars indicate wells where hydrofracturing commenced within 10 days prior to the occurrence of an earthquake. (b) Time series of monthly rates of produced water, produced gas (BOE, 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, injected water for the region mapped in (a), and timing (stars) of hydrofracturing operations within 10 km of earthquake epicenters. Earthquake magnitudes are plotted with respect to time.

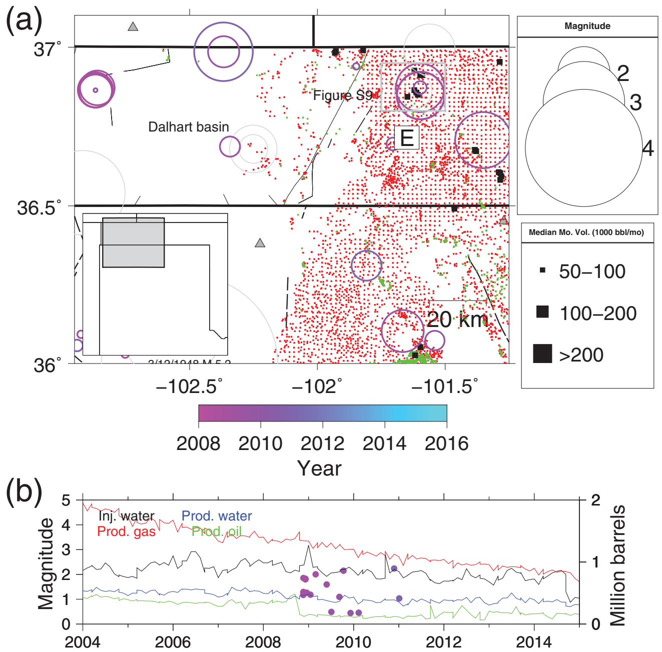


▲ **Figure 9.** (a) Map of the western Texas Panhandle region (see Fig. 3), showing earthquakes (circles) in cluster "D," wastewater injection wells (filled squares), and production wells (red and green dots). (b) Time series of monthly rates of produced water, produced gas (BOE, 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, and injected water for the region mapped in (a). This mapped region includes numerous injection wells not mapped because the median monthly injection rates are less than 50,000 bbl/mo.

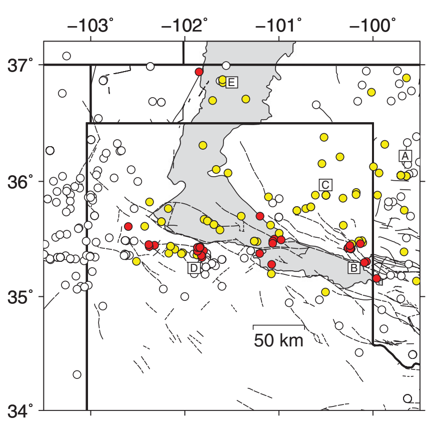
instruments in the last several decades, making it difficult to evaluate causation, we nonetheless apply a question-based scoring system similar to other previous investigations of induced seismicity in Texas (Davis and Frohlich, 1993; Davis *et al.*, 1995; Frohlich *et al.*, 2016). We follow from those studies and more directly, the latter, most recent study (Frohlich *et al.*, 2016) and pose questions concerning: timing (QT: Do earthquakes in this location begin occurring only after the commencement of petroleum production or fluid injection operations?); spatial correlation (QS: Are epicenters spatially correlated with production or injection operations?); depth (QD: Is information available concerning hypocentral depth, and does this information suggest that the earthquake occurred at or near production or injection depths?); faulting (QF: Is the earthquake near a mapped fault, or is it one of a linear group of epicenters delineating a fault?); and published analysis (QP: Is there a credible published paper linking the earthquake to production or injection operations?). The scoring rubric is detailed in the Ⓔ electronic supplement, and the results of scoring are included as Ⓔ Tables S4 and S5. We provide a final summary figure that summarizes our findings (Fig. 11).

DATA AND RESOURCES

Records from seismograph stations primarily from the EarthScope Transportable Array (TA), the Oklahoma Geological Survey (OGS), and other sources were obtained from publicly available sources maintained by the Incorporated Research Institutions for Seismology (IRIS) Data Management Center, including seismic networks TA (doi: 10.7914/SN/TA), OK (doi: 10.7914/SN/OK), XR (doi: 10.7914/SN/XR), and US (doi: 10.7914/SN/US). In Texas, a state agency called the Railroad Commission of Texas regulates oil and gas drilling and production. Information about well locations, depths, permitting history, and monthly production and injection rates is archived by the Railroad Commission and publicly available



▲ **Figure 10.** (a) Map of the Oklahoma Panhandle region (see Fig. 3), showing earthquakes (circles) in cluster E, wastewater injection wells (filled squares), and production wells (red and green dots). (b) Time series of monthly rates of produced water, produced gas (BOE, 5800 ft^3 of gas has the energy equivalency of a barrel of oil), produced oil, and injected water for the region mapped in the top panel. Light gray box near cluster E indicates the area for Ⓔ Figure S9.



▲ **Figure 11.** Map of earthquakes (circles) in Ⓔ Tables S1 and S3, ranked by the subjective question-based method of Frohlich *et al.* (2016), with colors showing the strength of available evidence (see Ⓔ Tables S4 and S5), indicating that each may have been induced by oil and gas production, wastewater disposal, or hydraulic fracturing: white, score 0.0–1.0 (event not induced, or very little evidence available); yellow, score 1.5–2.0 (event possibly induced); red, score 2.5–3.0 (event probably induced). No Panhandle earthquakes earned ranks of 4.0 or greater (event almost certainly induced). Mapped faults are from Ewing (1990) and Marsh and Holland (2016) and the Panhandle-Hugoton field (shaded gray). Earthquake clusters "A–E" discussed throughout the text are also labeled.

online. For this study, we utilized Railroad Commission data as compiled by IHS, Inc. We downloaded FracFocus data to determine time and locations of hydraulic fracturing operations from https://fracfocus.org/ (last accessed December 2017).

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REFERENCES

Bartlett, N. D. (1982). Discovery of the Panhandle oil and gas field, in *Panhandle Petroleum*, B. D. Weaver (Editor), Panhandle-Plains Historical Soc., Canyon, Texas.

Davis, S. D., and C. Frohlich (1993). Did (or will) fluid injection cause earthquakes? Criteria for a rational assessment, *Seismol. Res. Lett.* **64,** 207–224.

Davis, S. D., P. A. Nyffenegger, and C. Frohlich (1995). The 9 April 1993 earthquake in south-central Texas: Was it induced by fluid withdrawal?, *Bull. Seismol. Soc. Am.* 85**,** 1888–1895.

Docekal, J. (1970). Earthquakes of the stable interior, *Ph.D. Dissertation*, University of Nebraska, 2.

Ellsworth, W. L. (2013). Injection-induced earthquakes, *Science* **341,** 1225924, doi: 10.1126/science.1225942.

Ewing, T. (1990). *Tectonic Map of Texas*, Scale 1:750,000, University of Texas Bureau Economic Geology, Austin, Texas.

Frohlich, C. (2012). Two-year survey comparing earthquake activity and injection well locations in the Barnett Shale, Texas, *Proc. Natl. Acad. Sci. Unit. States Am.* **109,** 13,934–13,938, doi: 10.1073/pnas.1207728109.

Frohlich, C., and M. Brunt (2013). Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the M_w 4.8 20 October 2011 earthquake, *Earth Planet. Sci. Lett.* **379,** 53–63, doi: 10.1016/j.epsl.2013.07.025.

Frohlich, C., and S. D. Davis (2002). *Texas Earthquakes*, Univ. Texas Press, Austin, Texas, 275.

Frohlich, C., H. DeShon, B. Stump, C. Hayward, M. J. Hornbach, and J. I. Walter (2016). A historical review of induced earthquakes in Texas, *Seismol. Res. Lett.* **87,** no. 4, doi: 10.1785/0220160016.

Frohlich, C., W. L. Ellsworth, W. A. Brown, M. Brunt, J. H. Luetgert, T. MacDonald, and S. Walter (2014). The 17 May 2012 *M* 4.8 earthquake near Timpson, east Texas: An event possibly triggered by fluid injection, *J. Geophys. Res.* **119,** 581–593, doi: 10.1002/2013JB010755.

Frohlich, C., J. Glidewell, and M. Brunt (2012). Location and felt reports for the 25 April 2010 m_{bLg} 3.9 earthquake near Alice, Texas: Was it induced by petroleum production?, *Bull. Seismol. Soc. Am.* **102,** 457–466, doi: 10.1785/0120110179.

Frohlich, C., C. Hayward, B. Stump, and E. Potter (2011). The Dallas-Fort Worth earthquake sequence: October 2008 through May 2009, *Bull. Seismol. Soc. Am.* **101,** 327–340, doi: 10.1785/0120100131.

Frohlich, C., J. I. Walter, and J. F. W. Gale (2015). Analysis of transportable array (USArray) data shows earthquakes are scarce near injection wells in the Williston basin, 2008–2011, *Seismol. Res. Lett.* **86,** 492–499.

Galloway, W. E., T. E. Ewing, C. M. Garrett, N. Tyler, and D. G. Bebout (1983). *Atlas of Major Texas Oil Reservoirs*, Univ. Texas Bur. Econ. Geol., Austin, Texas.

Goldstein, A. G., and D. A. McGookey (1982). Minor fault motions in relation to late Paleozoic tectonics of the Wichita-Amarillo uplift, *Geol. Soc. Am. Abstr. Progr.* **14,** 111–112.

Gordon, D. (1988). Revised instrumental hypocenters and correlation of earthquake locations and tectonics in the central United States, *U.S. Geol. Surv. Profess. Pap. 1364*.

Gupta, H. K. (2002). A review of recent studies of triggered earthquakes by artificial reservoirs with special emphasis on earthquakes in Koyna, India, *Earth Sci. Rev.* **58,** 279–310.

Herrmann, R. B. (1979). Surface wave focal mechanisms for eastern North American earthquakes with tectonic implications, *J. Geophys. Res.* **84,** 3543–3552.

Herrmann, R. B., H. M. Benz, and C. J. Ammon (2011). Monitoring the earthquake source process in North America, *Bull. Seismol. Soc. Am.* **101,** no. 6, 2609–2625, doi: 10.1785/0120110095.

Hornbach, M. J., H. R. DeShon, W. L. Ellsworth, B. W. Stump, C. Hayward, C. Frohlich, H. R. Oldham, J. E. Olson, M. B. Magnani, C. Brokaw, *et al.* (2015). Causal factors for seismicity near Azle, Texas, *Nature Comm.* **6,** doi: 10.1038/ncomms7728.

Hough, S. E., and M. Page (2016). Potentially induced earthquakes during the early twentieth century in the Los Angeles basin, *Bull. Seismol. Soc. Am.* **106,** 2419–2435, doi: 10.1785/0120160157.

Justinic, A. H., B. Stump, C. Hayward, and C. Frohlich (2013). Analysis of the Cleburne, Texas earthquake sequence from June 2009 to June 2010, *Bull. Seismol. Soc. Am.* **103,** 3083–3093, doi: 10.1785/0120120336.

Keranen, K. M., H. M. Savage, G. A. Abers, and E. S. Cochran (2013). Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence, *Geology* **41,** 699–702, doi: 10.1130/G34045.1.

Keranen, K. M., M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge (2014). Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection, *Science* **345,** 448–451, doi: 10.1126/science.1255802.

Kosters, E. C., D. G. Bebout, S. J. Seni, C. M. Garrett, L. F. Brown, H. S. Hamlin, S. P. Dutton, S. C. Ruppel, R. J. Finley, and N. Tyler (1989). *Atlas of Major Texas Gas Reservoirs*, University of Texas Bureau of Economic Geology, Austin, Texas.

Lund Snee, J.-E., and M. Zoback (2016). State of stress in Texas: Implications for induced seismicity, *Geophys. Res. Lett.* **43,** 10,208–10,212, doi: 10.1002/2016GL070974.

Marsh, S., and A. Holland (2016). Comprehensive fault database and interpretive fault map of Oklahoma, 2 plates with supplement, *Oklahoma Geological Survey Open-File Rept. OF2-2016*.

Pippin, L. (1970). Panhandle-Hugoton Field, Texas-Oklahoma-Kansas—The first fifty years, in *Geology of Giant Oil Fields*, M. T. Halbouty (Editor), AAPG Memoir, Vol. 14, 204–222.

Pratt, W. E. (1926). An earthquake in the Panhandle of Texas, *Bull. Seismol. Soc. Am.* **16,** 146–149.

Reagor, B. G., C. W. Stover, and S. T. Algermissen (1982). Seismicity map of the state of Texas, *U.S. Geol. Surv. Map MF-1388*, 2 sheets, scale 1:1,000,000.

Scales, M. M., H. R. DeShon, M. B. Magnani, J. L. Walter, L. Quinones, T. L. Pratt, and M. J. Hornbach (2017). A decade of induced slip on the causative fault of the 2015 M_w 4.0 Venus earthquake, northeast Johnson County, Texas, *J. Geophys. Res.* **122,** 7879–7994, doi: 10.1002/2017JB014460.

Sellards, E. H. (1939). The Borger, Texas, earthquake of June 19, 1936: Austin, *University of Texas Publ. Number 3945*, 699–704.

Shurbet, D. H. (1969). Increased seismicity in Texas, *Texas J. Sci.* **21,** 37–41.

Smith, J. C. (2017). *Panhandle Field, Handbook of Texas Online*, available at http://www.tshaonline.org/handbook/online/articles/dop01 (last accessed December 2017).

Sorenson, R. P. (2005). A dynamic model for the Permian Panhandle and Hugoton Fields, western Anadarko basin, *Am. Assoc. Petr. Geol. Bull.* **89,** no. 7, 921–938.

von Hake, C. A., and W. K. Cloud (1968). U.S. earthquakes 1966, Washington, D.C., *U. S. Coast Geod. Surv.*, 110.

Walsh, R. R., and M. D. Zoback (2015). Oklahoma's recent earthquakes and saltwater disposal, *Sci. Adv.* **1,** e1500195, doi: 10.1126/sciadv.1500195.

Walter, J. I., J. C. Chang, and P. J. Dotray (2017). Foreshock seismicity suggests gradual differential stress increase in the months prior to the 3 September 2016 M_w 5.8 Pawnee earthquake, *Seismol. Res. Lett.* **88,** no. 4, doi: 10.1785/0220170007.

Walter, J. I., P. J. Dotray, C. Frohlich, and J. F. W. Gale (2016). Earthquakes in northwest Louisiana and the Texas–Louisiana border possibly induced by energy resource activities within the Haynesville shale play, *Seismol. Res. Lett.* **87,** no. 2A, doi: 10.1785/0220150193.

Weingarten, M., S. Ge, J. W. Godt, B. A. Bekins, and J. L. Rubinstein (2015). High-rate injection is associated with the increase in U.S. mid-continent seismicity, *Science* **348,** 1336–1340.

Woollard, G. P. (1968). A catalog of earthquakes in the United States prior to 1925, Based on Unpublished Data Compiled by Harry Fielding Reid and Published Sources Prior to 1930, *Hawaii Institute of Geophysics, Data Rept. 10*, University of Hawaii, unpaginated.

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