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A Historical Review of Induced Earthquakes in Texas

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ABSTRACT

In Texas, earthquakes have occurred in close association with activities accompanying petroleum production since 1925. Here we develop a five-question test to categorize individual events as "tectonic," "possibly induced," "probably induced," or "almost certainly induced." In Texas, the probably induced and almost certainly induced earthquakes are broadly distributed geographically—in the Fort Worth basin of north Texas, the Haynesville Shale play area of east Texas, along the Gulf Coast in south Texas, and the Permian basin of west Texas. As the technologies applied to manage petroleum fields have evolved, induced earthquakes have been associated with different practices. In fields being driven by primary recovery prior to 1940, earthquakes occurred in fields extracting high volumes of petroleum from shallow strata. Subsequently, as field pressures decreased and secondary recovery technologies became common, earthquakes also occurred in association with waterflooding operations. Since 2008, the rate of earthquakes with magnitudes greater than 3 has increased from about 2 events/yr to 12 events/yr; much of this change is attributable to earthquakes occurring within a few kilometers of wastewater disposal wells injecting at high monthly rates. For three sequences monitored by temporary local seismograph networks, most hypocenters had focal depths at and deeper than the depth of injection and occurred along mapped faults situated within 2 km of injection sites. The record clearly demonstrates that induced earthquakes have been broadly distributed in several different geographic parts of Texas over the last 90 years.

Online Material: Earthquake catalogs and a figure of focal mechanisms.

INTRODUCTION

There has been widespread recognition among seismologists since the 1960s that wastewater injection and other activities commonly associated with petroleum production can sometimes induce earthquakes (Healy *et al.*, 1968; Nicholson and Wesson, 1990; Suckale, 2009). In recent years, there has been a renaissance of interest in induced earthquakes, beginning after October–November 2008, when 10 felt earthquakes occurred near an injection well on the Dallas–Fort Worth (DFW) airport (Frohlich *et al.*, 2011). The events in north Texas were subsequently followed by noticeable increases in the occurrence rate of earthquakes elsewhere in the midwestern United States (Ellsworth, 2013), especially in Oklahoma (Keranen *et al.*, 2014; Walsh and Zoback, 2015), Arkansas (Horton, 2012), and other regions in Texas (Fig. 1). There have been 162 Texas earthquakes having magnitudes of 3 or greater occurring since 1975 and reported by the National Earthquake Information Center (NEIC) and the International Seismological Centre (ISC) (see Ⓔ Table S1 available in the electronic supplement to this article); of these, 94 have occurred since 2008.

Few geographic regions have had a petroleum industry for as long as, or as vigorous as, Texas. Thus, a review of Texas earthquakes associated with petroleum production activities is useful for comparison with induced earthquakes elsewhere and provides insight about how this phenomenon changes over time scales of decades or greater. One objective of this review is to assemble the available evidence concerning induced Texas earthquakes, including difficult-to-find publications describing older events.

Another objective is to evaluate and categorize individual Texas earthquakes using a standardized set of criteria. Toward this end, we apply a new five-question test to evaluate the strength of evidence suggesting an earthquake is induced. This five-question test is based on similar tests proposed some twenty years ago (see the Appendix). However, we simplified the questions to apply to both injection- and extraction-induced earthquakes and removed questions relating to subsurface pressures and geomechanical modeling, because this information is available for only a small fraction of reported earthquakes. From scoring the answers to these questions, we categorize individual earthquakes as "almost certainly induced," "probably induced," "possibly induced," or "tectonic." In the remainder of this review, for simplicity we will use the term "induced" collectively for earthquakes categorized as "almost certainly induced" and "probably induced."

In this review, we shall not discuss the Texas earthquakes categorized as "tectonic," because these are reviewed elsewhere

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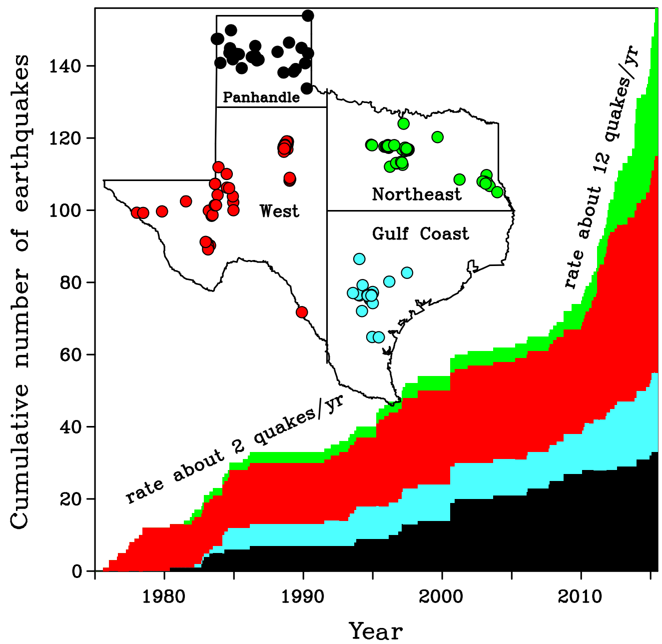
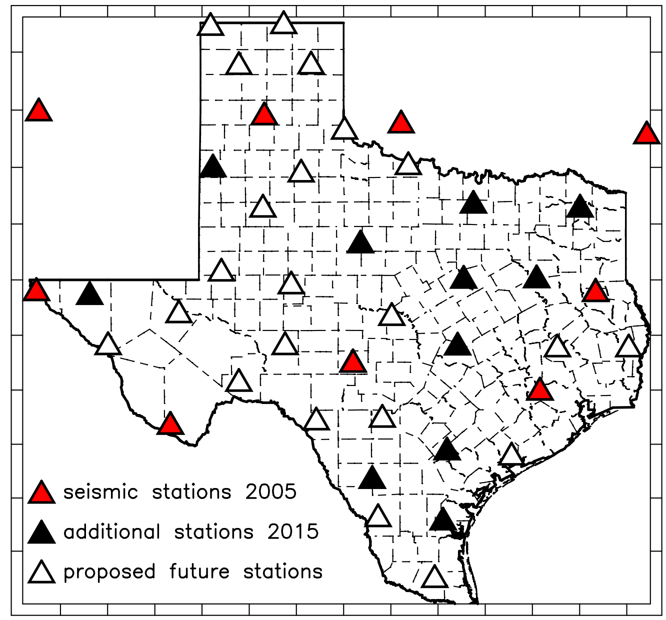


▲ **Figure 1.** Earthquakes in Texas with magnitudes of 3 or greater since 1975 and regions where they occurred. Earthquakes are as cataloged in Ⓔ Tables S1 and S4. Note that beginning about 2008, the rate increased from about 2 earthquakes/yr to about 12 earthquakes/yr, and this increase occurred in the Northeast, Gulf Coast, and west Texas regions, but not in the Panhandle. The color version of this figure is available only in the electronic edition.

(Frohlich and Davis, 2002). These tectonic events include Texas' two largest historical earthquakes, both having magnitudes of about 6, which occurred on 16 August 1931 and 14 April 1995 in west Texas.

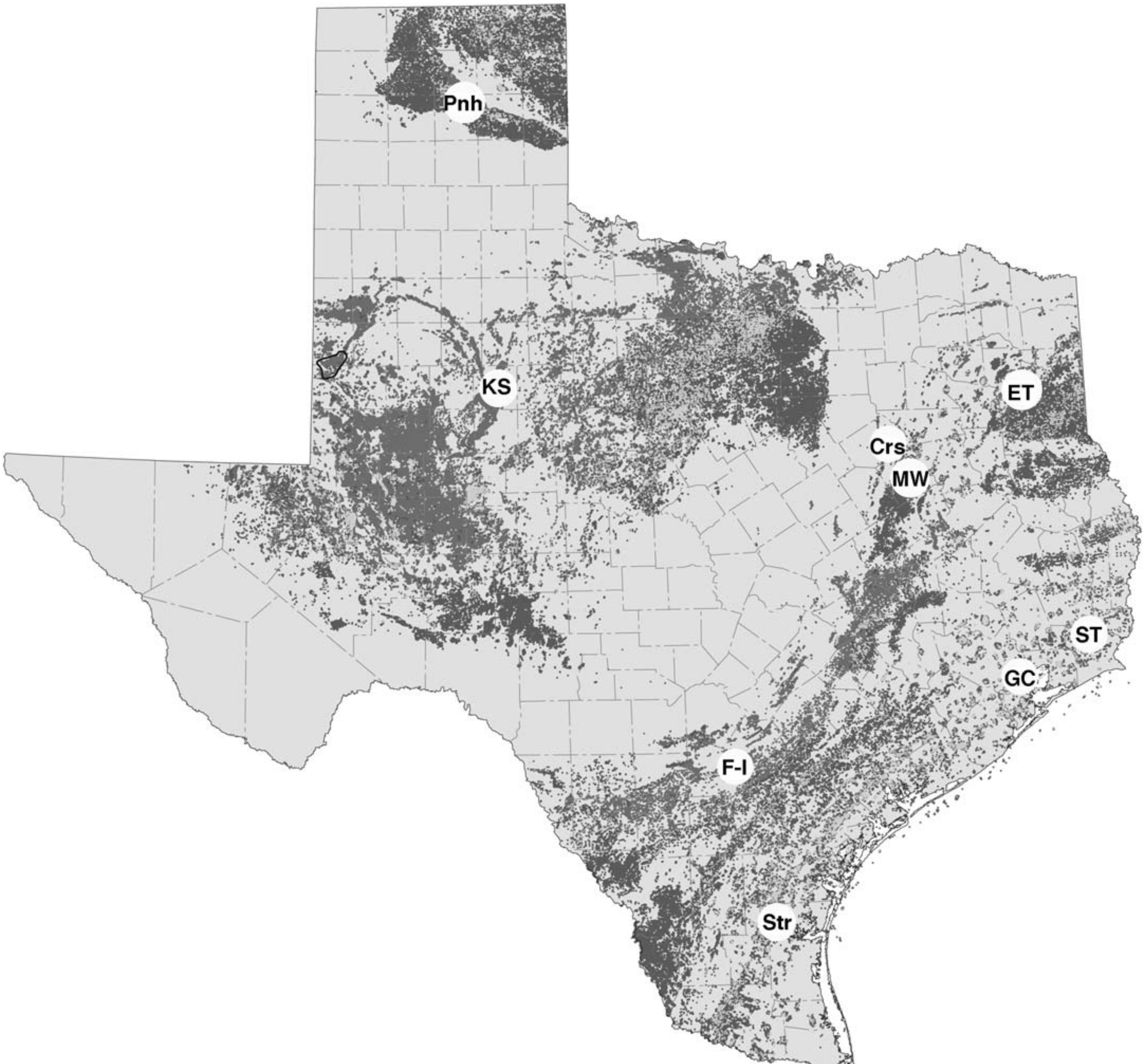
HISTORICAL BACKGROUND

Texas earthquakes associated with petroleum operations and here categorized as induced have occurred since 1925, but the amount and quality of data available to evaluate a possible causal relationship has changed considerably over time. Prior to about 1970, Texas had few seismograph stations, and much of the available information came from felt-report studies. As late as 2005, there were only six continuously operating seismic stations in Texas providing publicly available data (Fig. 2), and thus epicenters reported by the NEIC typically had uncertainties of 5–10 km or more (Frohlich *et al.*, 2011; Ellsworth, 2013). At present, there are 17 permanent seismograph stations providing continuous real-time waveform data; and, in 2015 the Texas legislature, in response to concern about induced earthquakes, funded a program to install 22 additional stations and establish a statewide monitoring network (Texas House Bill 2, 2015). This legislative action and the anticipated expansion of seismic monitoring in Texas provide additional motivation to categorize previously recorded earthquake activity, because we are presently transitioning to an era in which Texas seismicity will be more effectively monitored.



▲ **Figure 2.** Texas seismograph stations. As recently as 2005, Texas had only six three-component, broadband seismograph stations providing continuous, publicly available data, and there were three additional stations in neighboring states. Eleven additional Texas stations were operational by 2015, and 22 more are projected for installation as part of a state network funded by the Texas legislature in 2015. In addition to these broadband stations, Oklahoma, Arkansas, and New Mexico presently operate statewide seismograph networks to monitor regional seismic activity. The color version of this figure is available only in the electronic edition.

Petroleum production has been broadly distributed across Texas for almost a century (Fig. 3) (Hinton and Olien, 2002; Olien, 2010). The first oil field in Texas with a substantial economic impact was in 1894 near Corsicana, situated about midway between Dallas and Mexia in northeast Texas. The famed Spindletop strike was in 1901, close to Beaumont along the Gulf Coast near the Louisiana border. The Goose Creek Field, south of Houston on the Gulf Coast, opened in 1908 and reached maximum production in 1918. During the 1920s, oil production continued along the Gulf Coast and in northeast Texas. The Mexia and Wortham Fields were discovered in 1920 and 1924. Fields also began producing at numerous locations in the Panhandle and the Permian basin. The Panhandle Field began producing commercially in 1921; several fields in west Texas opened between 1921 and 1929. In the 1930s and subsequently, development of new fields across Texas continued, and earthquakes have been associated with several of these fields: 1930 marked the discovery of the East Texas Field, then one of the largest in the world, and probably responsible for the 1957 Gladewater earthquake; the Stratton Field, apparently responsible for the 1997 and 2010 Alice earthquakes, opened in 1938. Also, the Cogdell Field opened in 1949; the Imogene and Fashing Fields opened in 1944 and 1958; felt earthquakes began occurring in all three fields in the 1970s, and have contiued up to the present (see

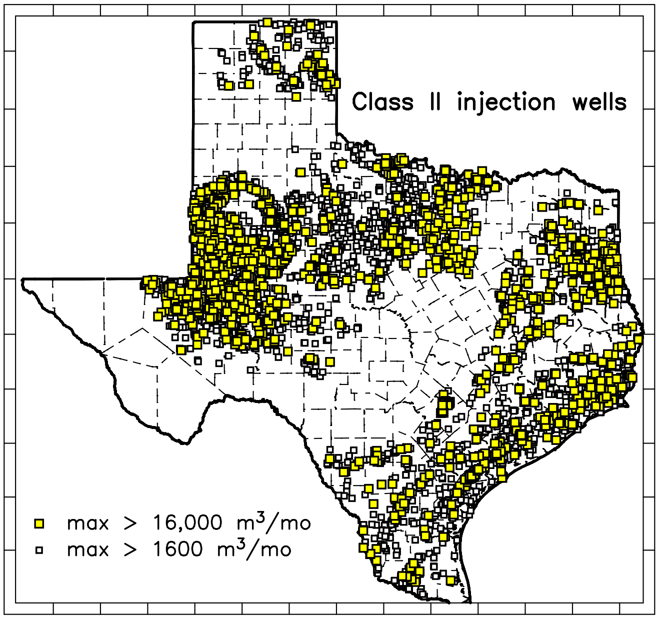


▲ **Figure 3.** Texas oil and gas wells. The map shows the historically significant petroleum fields (labeled) mentioned in the text and active oil and gas wells as compiled in 2013 by the Texas Bureau of Economic Geology from data supplied by the Texas Railroad Commission. Field key: Crs, Corsicana; ET, East Texas; F-I, Fashing–Imogene; GC, Goose Creek; KS, Kelly–Snyder; MW, Mexia–Wortham; Pnh, Panhandle; ST, Spindletop; and Str, Stratton.

the Results: Assessment of Induced Earthquakes in Four Regions of Texas section).

The production of oil and gas is often accompanied by the extraction of significant amounts of connate water (water trapped in sedimentary pore spaces). Since the 1930s much of this produced water has been reinjected into the producing reservoir to improve hydrocarbon recovery. Two such methods are re-injection to maintain reservoir pressure, and waterflooding operations that move oil laterally from water-injection wells to producing wells. Finally, the process of injecting chemicals and/or gases such as CO_2 to bring about tertiary recovery or enhanced oil recovery is widespread nowadays and has been in use for decades. These technologies are contrasted with the primary recovery phase of production, when natural subsurface pressures are sufficient to produce petroleum without waterflooding or other treatments.

In other fields, no commercial benefit is achieved from injecting into the producing reservoir; and, because produced water is often highly saline, alternate means of water disposal must be employed. Most often, this is accomplished by injec-



▲ **Figure 4.** Location and maximum monthly injection volumes for active injection wells in Texas. Figure redrawn from Frohlich (2013). The color version of this figure is available only in the electronic edition.

tion into specially designed and permitted water disposal wells. These disposal wells are numerous, and many have been in operation for decades; there are currently tens of thousands of active disposal wells in Texas (Fig. 4).

Much of the present concern about induced seismicity focuses on the development of so-called unconventional sources of petroleum—gas or oil that is bound up in strata having permeabilities too low to allow fluid to flow easily. The combination of the technologies of horizontal drilling and hydrofracturing made it possible to selectively increase subsurface permeability and thus exploit unconventional sources. Both technologies were developed more than 60 years ago but only began to be exploited on a massive scale in Texas since about 2003 in the Barnett Shale of northeast Texas, since about 2008 in the Haynesville Shale of east Texas, since about 2009 in the Eagle Ford of south Texas, and since about 2011 in the Permian basin of west Texas. Hydrofracturing in a horizontally drilled well typically requires water volumes two to three times greater than in a vertical well (Nicot and Scanlon, 2012); and, when hydrofractured wells enter the production phase, much of the injected water returns to the surface as wastewater that requires disposal. For the most part, induced seismicity associated with unconventional petroleum development is associated with wastewater disposal, not the hydrofracturing process itself.

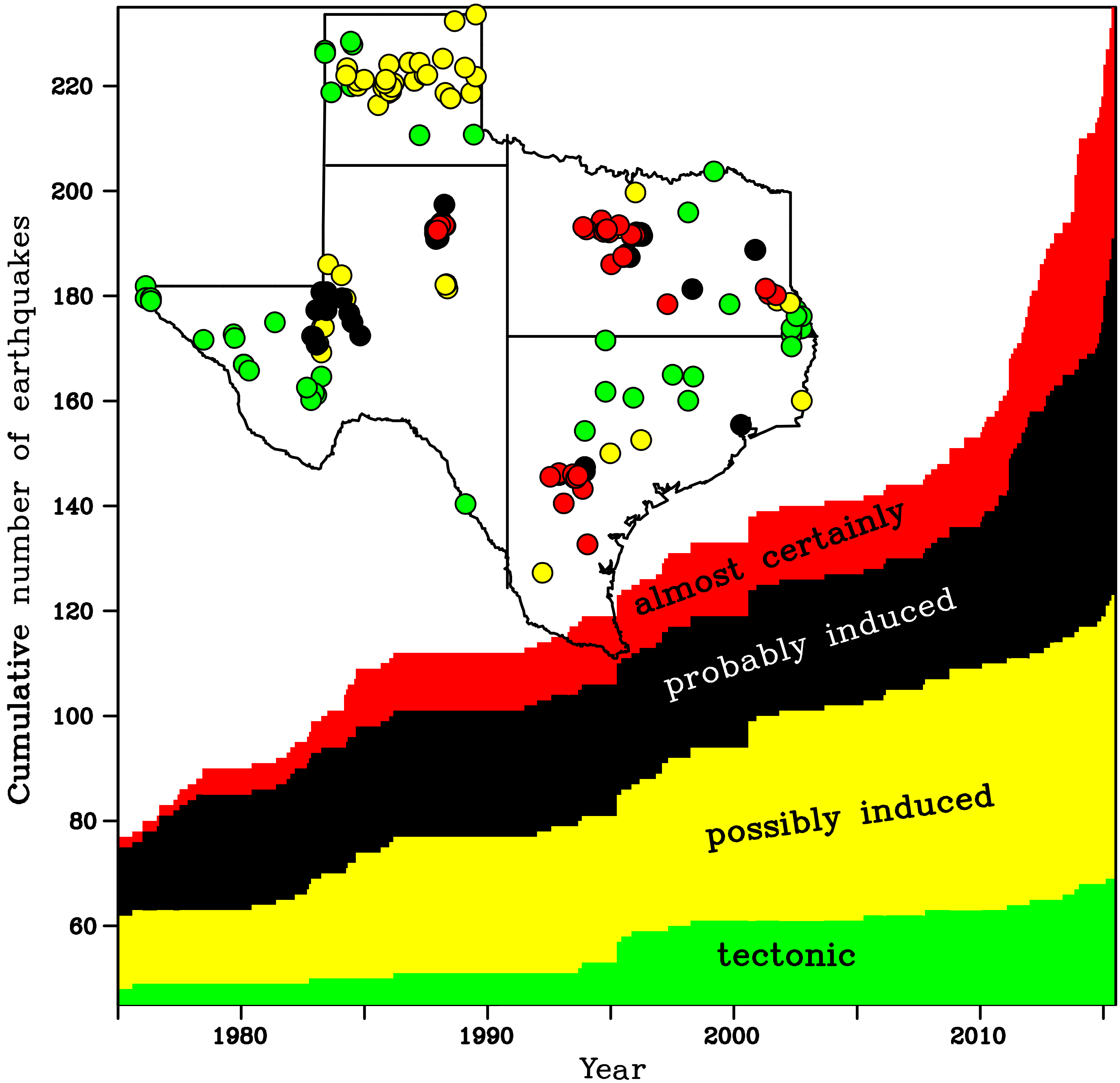
METHODS: ASSESSING EVIDENCE THAT AN EARTHQUAKE IS INDUCED

In the historical catalog, we categorize each earthquake as tectonic, possibly induced, probably induced, or almost certainly induced (Ⓔ Tables S1 and S2). To assess the strength of evidence suggesting that individual earthquakes might be induced, we utilize a five-question test (Appendix), scoring 1.0, 0.5, and 0.0 for answers of "Yes," "Possibly," or "No" and then summing the scores. Each of the five questions concerns a different category of evidence supporting the assertion that an earthquake is induced: Question QT concerns timing: Do the earthquakes occur only after potentially influential human activities begin? Question QS concerns spatial relationships: Are the earthquakes and human activities close enough so that a causal relationship is plausible? Question QD concerns depth of focus: Is there evidence from the pattern of felt reports, surficial features, or credible hypocentral locations that is consistent with a relatively shallow depth and a possible causal relationship? Question QF concerns faulting: Near the epicenter, are there known faults, either as mapped or as inferred from linear groupings of epicenters, that might support an earthquake, or enhance movement of fluids? Question QP concerns published scientific analysis: Have credible scientists investigated these events and concluded a human cause is plausible?

This question-based method for assessing the evidence is similar to methods proposed previously (Davis and Frohlich, 1993; Davis *et al.*, 1995). We have reworded some questions to make them more general so that a single test applies both to earthquakes induced by injection and to those induced by other mechanisms. We no longer include questions related to subsurface pressures and modeling; this information is available for few events and, when reported, often relies on somewhat arbitrary (and arguable) assumptions about subsurface structure and flow properties. In addition, the scoring for the proposed five-question test (Appendix) already gives adequate credit for analysis and modeling, because this often contributes to QP (published investigations) and sometimes to QS and QD (epicentral location and focal depth).

As with locations, the categorizations of earthquakes in Ⓔ Tables S1 and S2 are subject to change in response to future research. For example, for earthquakes in west Texas and the Panhandle, the scores will change if more detailed information becomes available concerning regional faulting, focal depths, or regional injection and production practices. The analysis of earthquakes occurring near Irving and Dallas, Texas, since 2014 is not yet complete, so at present question QP concerning publication receives a score of 0.0. Furthermore, questions QT and QS (time and space) receive scores of 0.5 because there was a production well (now shut-in) near the epicenters; these scores may change to either 1.0 or 0.0 if ongoing analysis determines whether or not it is plausible this well induced seismic activity.

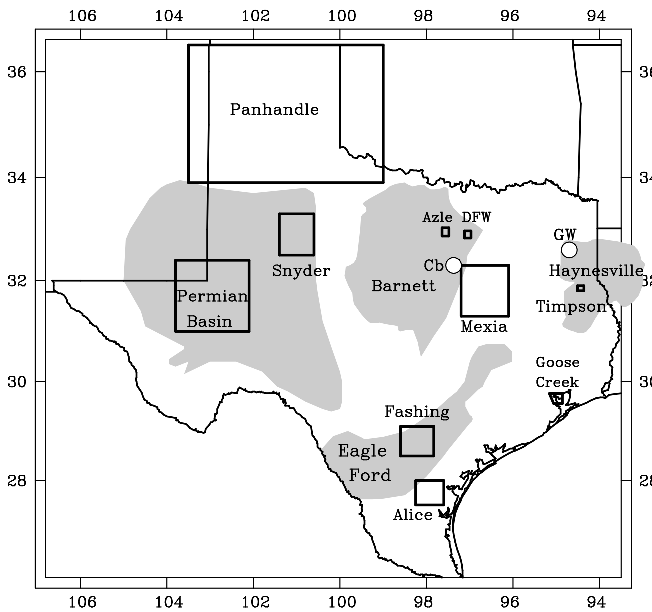
The summary assignment categorizing earthquakes—with scores of 4.0–5.0 as almost certainly induced, 2.5–3.5 as probably induced, 1.5–2.0 as possibly induced, and 0.0–1.0 as tectonic—is arbitrary. In geographic locations other than Texas, other summary characterizations may be appropriate. In Texas, because there is seldom credible information about focal depth in the absence of any field study or local network deployment, uninvestigated earthquakes are unlikely to receive summed scores higher than 3.5 and thus will not be characterized as almost certainly induced.



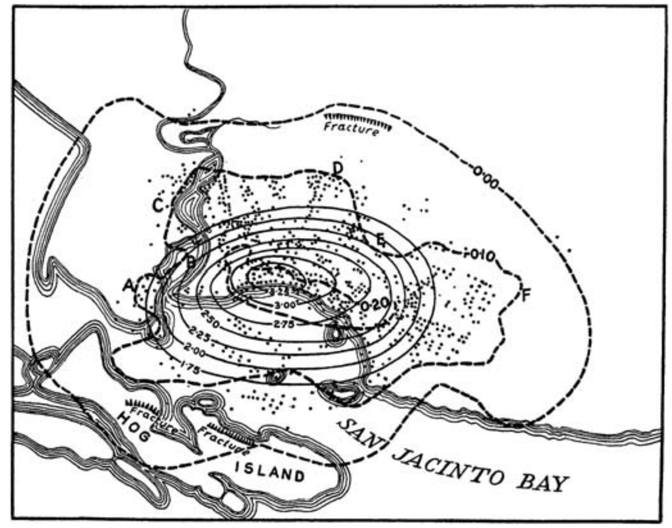
▲ **Figure 5.** Strength of evidence supporting an induced cause for Texas earthquakes 1847–2015. Earthquakes are as categorized in Ⓔ Tables S2 and S4, scored by the authors using the method described in the Appendix. The color version of this figure is available only in the electronic edition.

RESULTS: ASSESSMENT OF INDUCED EARTHQUAKES IN FOUR REGIONS OF TEXAS

By applying the five-question test and scoring system to our compilation of Texas earthquakes with reported magnitudes of 3 and greater (Ⓔ Tables S1 and S2), we find induced earthquakes occurring between 1925 and the present (Fig. 5). Some earthquakes are associated with fluid injection, whereas others are associated with production and/or fluid extraction. Most of these earthquakes are small (magnitude 4 or smaller); however, at least four have had magnitudes of 4.6 and higher. Altogether, for the 162 Texas earthquakes having magnitudes of 3 or greater and occurring between 1975 and 2015, we categorize 42 (26%) as almost certainly induced, 53 (33%) as probably induced, 45 (28%) as possibly induced, and the remaining 21 (13%) as tectonic. In the remainder of this section, we describe the most significant induced earthquakes and earthquake sequences in four different geographic regions of Texas.



▲ **Figure 6.** Map locations of earthquake sequences discussed in this review. Labeled rectangles indicate areas mapped in Figures 7–16. Circles labeled Cb and GW are locations of the 2009–2011 earthquakes near Cleburne and the 1957 earthquakes near Gladewater, respectively. Gray shaded areas indicate the extent of the Permian basin, the Barnett Shale, the Haynesville Shale producing area, and the Eagle Ford Shale producing area.



▲ **Figure 7.** Map of subsidence in the Goose Creek oil field, Texas. Between 1916 and 1925, more than a meter of subsidence, surface fractures, and felt earthquakes accompanied production of more than 16×10^6 m^3 of oil from this field east of Houston. Here, subsidence contours are in feet, and the dots are locations of oil wells. The total extent of subsidence area (dashed 0.00 contour line) is about 5 km. Figure reproduced from Pratt and Johnson, 1926, with permission from University of Chicago Press.

Texas Gulf Coast

Goose Creek, 1925: Probably Induced

Small earthquakes accompanied ground subsidence of up to a meter associated with the withdrawal of more than 16×10^6 m^3 of oil and water, beginning in 1916, from the Goose Creek Field along San Jacinto Bay east of Houston, now called Baytown (Figs. 6 and 7). None of the available sources lists specific dates for the occurrence of these earthquakes, but contemporary descriptions noted that they "shook the houses, displaced dishes, spilled water, and disturbed the inhabitants generally" (Pratt and Johnson, 1926, p. 581). Commercially important production in the Goose Creek Field came from sand lenses at depths of 1000–4000 ft (300–1200 m). In Pratt and Johnson (1926) and Yerkes and Castle (1976), there are maps of the subsided region, pictures of surface faults or "fractures," and discussion of the mechanics.

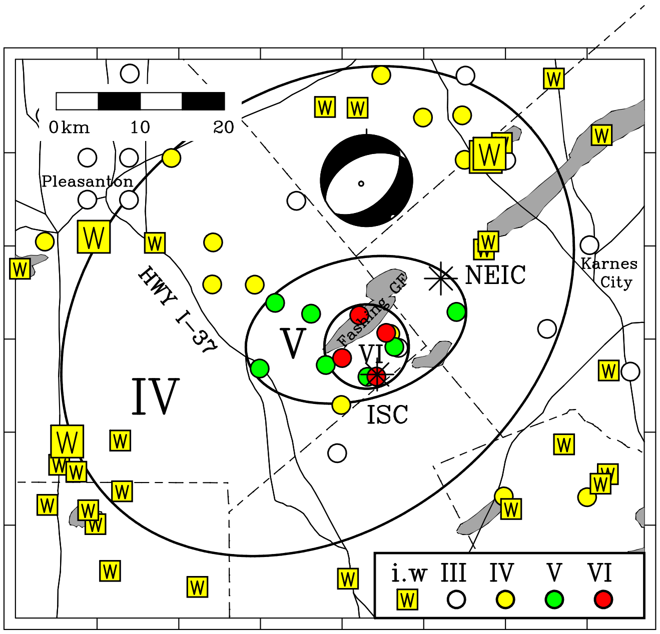
Because the subsidence submerged much of the land surface overlying the field to below sea level, the state of Texas, hoping to collect the revenues from oil produced, sued Humble Oil for the rights to the field, which, no longer being on land, was not subject to private ownership (Pratt and Johnson, 1926). The state lost the suit because the court ruled that the subsidence was an "act of man" caused by the extraction of oil and was not a natural event. Thus, one notable feature of the Goose Creek earthquakes is that there is a court ruling and a 90-year-old precedent supporting the assertion that oil and gas activities induce land subsidence and accompanying earthquakes in Texas.

Fashing, 1973–2012: Almost Certainly Induced

Since Christmas Eve (local time) in 1973, several felt earthquakes have occurred near Fashing in Atascosa County, Texas. Events include an m_{bLg} 3.6 on 23 July 1983 (Pennington *et al.*, 1986), an m_{bLg} 4.3 on 9 April 1993 (Davis *et al.*, 1995), and an M_w 4.8 on 20 October 2011 (Frohlich and Brunt, 2013). The highest felt intensities were reported as modified Mercalli intensity (MMI) VI, occurred in and near the Fashing gas field in both 1993 and 2011, and fell off to MMI III or less at distances beyond 30 km (Figs. 6 and 8). A focal mechanism for the 2011 earthquake (Herrmann *et al.*, 2011; Frohlich and Brunt, 2013) indicated normal faulting along a northeast–southwest-trending fault (see Fig. 8, Ⓔ Fig. S1, and Table S3).

Pennington *et al.* (1986) summarized the history of gas production at the Fashing Field. The Fashing Field is in the Edwards Limestone along the upthrown side of a normal fault. Production began in 1958 from horizons at 3.4 km depth; initial bottomhole pressure was 35.2 MPa in 1958, but by 1983 pressures along the fault had dropped to 7.1 MPa, or about 20% of the initial values. Their investigation concluded the Fashing earthquakes up to that time were related to fluid withdrawal (i.e., gas production operations).

Investigations of the subsequent earthquakes in 1993 and 2011 reached similar conclusions (Davis *et al.*, 1995; Frohlich and Brunt, 2013). Frohlich and Brunt (2013) noted that the 1973, 1993, and 2011 earthquakes all coincided with marked increases in extraction volumes of oil and water from wells in the region experiencing MMI V and greater during the 2011 earthquake. In the five years prior to the 2011 earthquake,

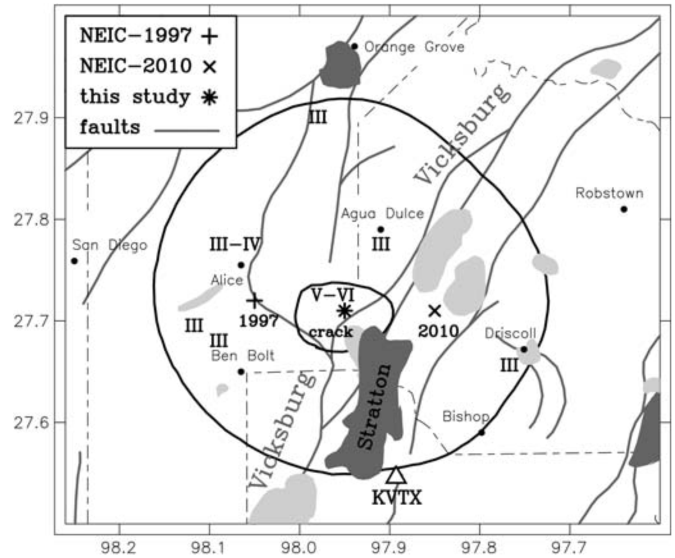


▲ **Figure 8.** Felt reports and injection disposal wells near the 20 October 2011 M_w 4.8 Fashing earthquake. Circles indicate the locations and modified Mercalli intensity (MMI) values of felt reports, squares are injection disposal wells, and gray areas are gas fields. Asterisks labeled "NEIC" and "ISC" indicate the epicenter as reported by the National Earthquake Information Center and the International Seismological Centre, respectively; the plotted focal mechanism for this event is as reported by St. Louis University (Herrmann *et al.*, 2011). The highest-intensity region of this earthquake was situated more than 15 km from the nearest active injections wells and thus is unlikely to be induced by injection. However, Frohlich and Brunt (2013) showed that earthquakes here in 1973, 1983, and this event followed increases in the rate of extraction of water and petroleum from wells situated within the MMI V–VI region shown here. This figure is modified from Frohlich and Brunt, 2013. The color version of this figure is available only in the electronic edition.

the nearest active injection disposal wells were 15 km and more distant from the epicentral region. The studies conclude that all the Fashing earthquakes are induced but caused by extraction, not injection.

Alice, 1997 and 2010: Almost Certainly Induced

Two nearly identical m_{bLg} 3.9 earthquakes occurred on 24 March 1997 (Bilich *et al.*, 1998) and 25 April 2010 (Frohlich *et al.*, 2012) near Alice, Texas, about 75 km west of Corpus Christi (Figs. 6 and 9). Their intensities reached MMI V–VI in a region about 10–20 km southeast of Alice and approximately along the mapped trace of the Vicksburg fault and the boundary of the Stratton oil and gas field, which has produced 76×10^9 m^3 of gas and about 16×10^6 m^3 of oil since production commenced in 1938. Analysis of secondary arrivals and surface waves suggested the earthquakes had focal depths of 3 km or less, the approximate depth of the producing Frio



▲ **Figure 9.** Felt report summary for the 25 April 2010 m 3.9 Alice earthquake. Labels of MMI levels III and V–VI indicate the locations where individuals provided felt information. Three individuals within the MMI V–VI isoseismal region reported experiencing MMI V or MMI VI. The location labeled crack indicates the reported location of a 1.6-km-long northeast–southwest crack following the 1997 earthquake. Symbols +, ×, and *, respectively, indicate the NEIC epicenters for the 1997 and 2010 earthquakes and the location for both events as determined by Frohlich *et al.* (2012). Dark and light gray areas are oil and gas fields, respectively; mapped faults are from Ewing (1990). Triangle labeled KVTX is location of seismograph station in Kingsville, Texas. Figure reproduced from Frohlich *et al.* (2012).

formation in the Stratton Field. Following the 1997 earthquake, one resident reported that a 1.6-km-long southwest–northeast-trending crack had appeared in fields within the highest-intensity region.

Evidence that supports an induced cause includes the absence of any previously reported regional earthquakes, the shallow focal depths, and the epicenters near the boundary of a field that has produced high volumes of oil and gas for many decades.

Elsewhere Along the Gulf Coast

Small felt earthquakes occurring in 1984 and subsequently have occurred in Atascosa County about 35 km northwest of Fashing, near Pleasanton and Jourdanton, coincident with the Imogene oil field. As in the Fashing Field, production in the Imogene Field is also from an upthrown normal fault, at 2.4 km depth, and began in 1944. Following the 1984 earthquake, a small local seismograph network recorded aftershocks that were "found to be at or near the fault contact of the producing horizon of the Imogene Field" (Pennington *et al.*, 1986, p. 940). This suggests these earthquakes are almost certainly induced, although caused by extraction, not injection.

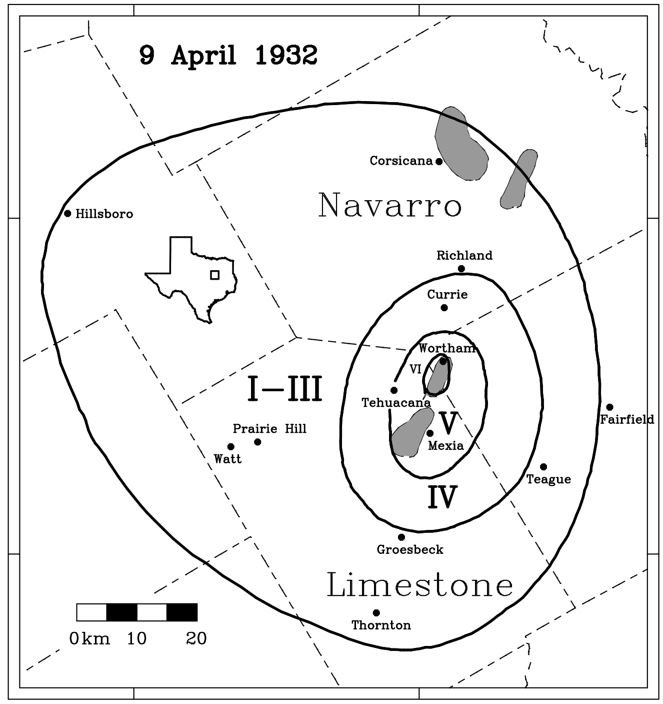
Felt earthquakes have also been reported in Falls City, Texas, about 20 km northeast of Fashing, in Karnes County (Olson and Frohlich, 1992; Davis *et al.*, 1995). These include a magnitude m_{bLg} 3.6 on 20 July 1991 and an m_{bLg} 4.3 on 7 April 2008. Although Olson and Frohlich (1992) suggested that the 1991 event might be caused by fluid withdrawal, Frohlich and Brunt (2013) noted that the 1991 quake followed an increase in injection beginning in 1990 at nearby disposal wells. Increases in both injection and production occurred prior to the 2008 earthquake. A focal mechanism for the 2008 earthquake (Herrmann *et al.*, 2011) indicated normal faulting along a northeast–southwest-trending strike (see Ⓔ Table S3 and Fig. S1). As suggested by all the investigations mentioned here, these earthquakes are probably induced.

Northeast Texas

Mexia-Wortham, 9 April 1932: Almost Certainly Induced

This earthquake, with an estimated magnitude of 4.0, shook down bricks from several chimneys in Wortham but was only barely perceptible to people at several towns about 20 miles away (Figs. 6 and 10). This indicates the focal depth must have been quite shallow. Sellards (1933) reported that the earthquake caused a crack that extended across the highway between the towns of Wortham and Mexia. The regions of highest intensities included the Wortham and Mexia Fields, which had produced more than 15×10^6 m^3 of oil at that time.

Sellards (1933, p. 111) noted that "...the fact that the tremor was centered in a region of large oil production lends force to the idea that the tremor may have been caused by adjustment in the land surface incident to operations in the oil fields," and subsequent publications have also reached this conclusion (Yerkes and Castle, 1976).



▲ **Figure 10.** Felt report summary for the 9 April 1932 magnitude of 4.0 Mexia–Wortham earthquake. Roman numerals are MMIs, and the dashed lines are county boundaries. The shaded regions are major oil fields established prior to 1932. The relatively high intensities (MMI VI) coinciding with the Wortham Field and the much lower intensities (III and less) at distances exceeding about 20 km suggest a shallow focal depth. Figure modified from Frohlich and Davis (2002) with permission from University of Texas Press.

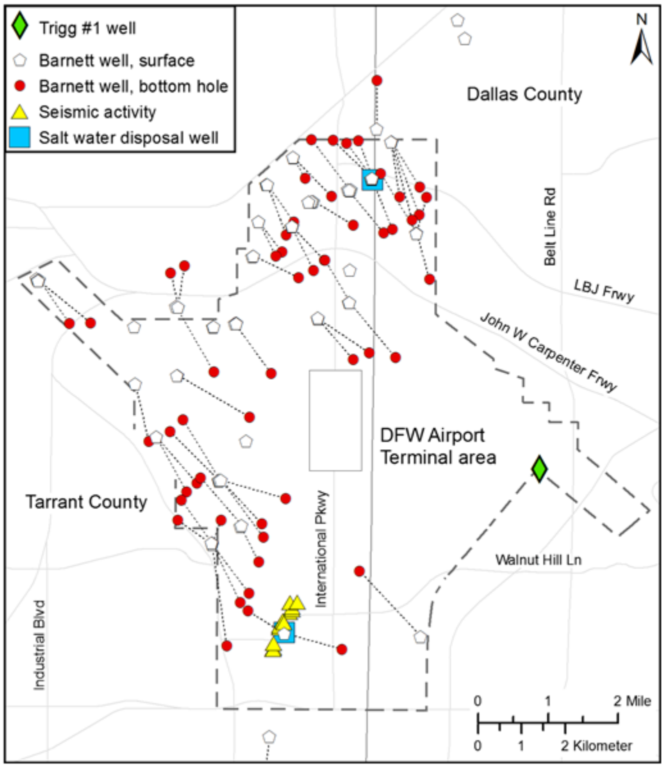
Gladewater, 19 March 1957: Probably Induced

A series of four earthquakes, the largest having magnitude 4.7, were felt most strongly between Gladewater and Longview and occurred directly above the northern part of the East Texas Field in the area of the highest density of wells. Frohlich and Davis (2002) presented arguments both for and against an induced cause, noting that "The East Texas Field was, at the time of discovery in 1930, the largest field in the Western Hemisphere. By [1957] more than 600×10^6 m^3 of oil had been extracted from the field. The relatively high magnitude and large felt area (45,000 km^2)... are difficult to explain if it was induced by fluid withdrawal. Moreover, it seems unlikely that a quake with magnitude as great as 4.7 would occur at the relatively shallow production depth of 1 km (pp. 31–32)." The available information does not provide accurate information about the epicenter or focal depth of this earthquake.

Unfortunately, there is no detailed published case history describing the 1957 Gladewater sequence and evaluating its relationship to regional petroleum operations; the two-page summary of Frohlich and Davis (2002, pp. 176–178) is the most comprehensive source available. Nevertheless, because (1) historical earthquakes are unknown at this location, (2) a huge volume of fluid had been removed from the east Texas Field, (3) fluid removal over decades-and-longer intervals appears to have induced many of the earthquakes elsewhere in Texas described above, and (4) published sources have suggested the Gladewater earthquakes may have been induced (Yerkes and Castle, 1976), we now categorize this sequence as probably induced.

Dallas–Fort Worth International Airport, 2008–2013: Almost Certainly Induced

Beginning on 30 October 2008, people living near the DFW International Airport reported experiencing felt earthquakes (Figs. 6 and 11). These were the first earthquakes known in the DFW metropolitan area in historical times (i.e., since about 1860). Scientists at Southern Methodist University (SMU) deployed a six-station seismograph network that recorded numerous aftershocks between November 2008 and January 2009. Analysis of these data (Frohlich *et al.*, 2011; Reiter *et al.*, 2012) indicated that all well-recorded events occurred at focal depths of about 4.5 km along an approximately 1-km-long northeast–southwest linear trend coinciding with a previously mapped fault. The epicenters were within about a kilometer of a wastewater disposal well on the DFW airport property. This



▲ **Figure 11.** Earthquakes, injection wells, and production wells at the Dallas–Fort Worth (DFW) International Airport. Triangles are the 11 earthquakes occurring in 2008 and 2009 and located using data collected by a six-station temporary network; squares are injection disposal wells; circles and white pentagons are bottom-hole and surface locations, respectively, of producing horizontal natural gas wells. Earthquake focal depths were ~4.5 km; their epicenters were within 0.5 km of a well that began injecting about 16,000 m^3/mo at 4.2 km depth, beginning about seven weeks before the first earthquake was reported. Figure reproduced from Frohlich *et al.* (2011). The color version of this figure is available only in the electronic edition.

well had begun injection operations only seven weeks before the first earthquakes occurred, injecting into the Ellenburger formation at rates of about 48,000 m^3/mo between 12 September 2008 and August 2009. Activity at the airport continued well after injection ceased in 2009; the largest earthquake with magnitude m_{bLg} 3.4 occurred on 30 September 2012.

About eight months after injection ceased, a second sequence of earthquakes began to the northeast along the extension of the northeast–southwest-trending linear cluster about 2 km from the injection well. Because this sequence began after injection ceased, Janska and Eisner (2012) suggest the entire DFW airport sequence may be tectonic in origin and unrelated to injection. However, the fact that earthquakes sometimes occur after injection ceases is well known (Healy *et al.*, 1968; Nicholson and Wesson, 1990; Suckale, 2009; Ellsworth, 2013). Thus, we and others (Frohlich *et al.*, 2011; National Research Council, 2012) conclude that the DFW airport earthquakes were induced because of the absence of historical seismicity prior to injection, the proximity of the injection well to a known mapped fault, the onset of activity only six weeks after injection commenced in 2008, and the earthquake depths at and below the depth of injection.

Cleburne, 2009–2012: Almost Certainly Induced

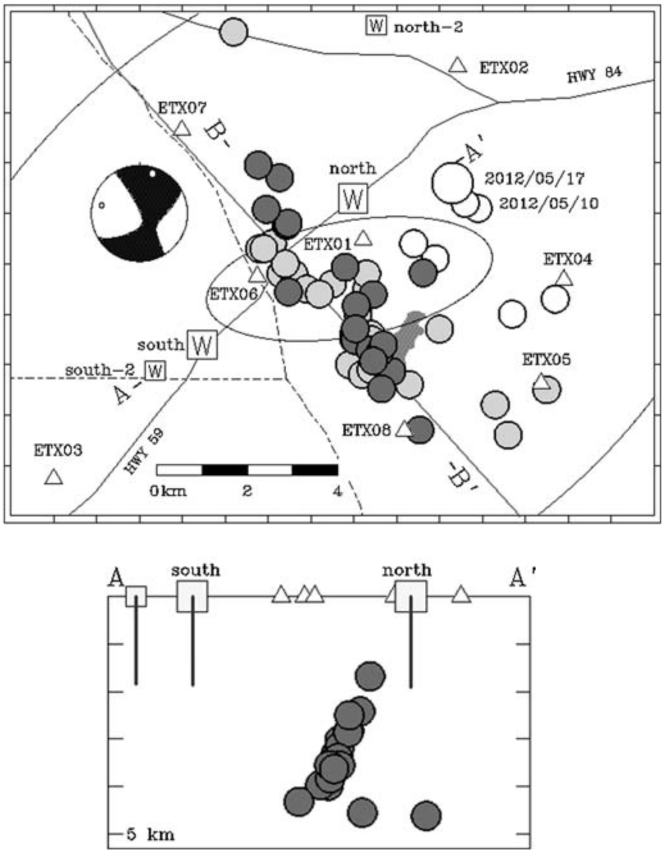
Beginning in June 2009, residents of Cleburne, situated about 60 km south of Fort Worth, reported experiencing felt earthquakes that continued until at least June 2012. The largest reported magnitude was m_{bLg} 3.5 for an earthquake on 24 June 2012. Scientists at SMU installed a five-station temporary network to record this activity (Justinic *et al.*, 2013) and were able to locate accurately 38 earthquakes occurring along a 2–3-km-long north–south-trending linear feature, with best-determined focal depths of 3.5–4.2 km. The centroid of these locations was 1.3 km from a saltwater disposal well that began injecting in 2007 at depths of 2.4–3.1 km, and 3.2 km distant from a well that injected at depths of 3.2–3.3 km from September 2005 through July 2009. We know of no mapped faults in the public archive for this location, but faulting throughout the oil and gas production layers in the Fort Worth basin in neighboring counties is not uncommon (Railroad Commission of Texas, 2015). Focal mechanisms determined for two events indicate normal faulting along a north–south-trending direction that corresponds to the linear trend of located events.

Because of the absence of historical seismicity prior to injection, the proximity of the injection wells, and the depths of some earthquakes depths near the depth of injection, we conclude this sequence is almost certainly induced.

Timpson, 2012–2014: Almost Certainly Induced

On 10 May 2012, an earthquake with M_w 3.9 occurred in east Texas a few kilometers southeast of Timpson (Figs. 6 and 12); on 17 May 2012, there was a larger M_w 4.8 event that produced intensities up to MMI VII. Waveform modeling for the 17 May mainshock was consistent with a focal depth of 4.5 km (Frohlich *et al.*, 2014). Focal mechanisms reported for this event indicated strike-slip faulting (Fig. 12, Ⓔ Fig. S1, and Table S3).

By February 2013, eight temporary seismograph stations had been installed (Frohlich *et al.*, 2014). These stations recorded numerous aftershocks with epicenters situated along a northwest–southeast-trending, southwest-dipping mapped fault that had been reported by Jackson (1982). Focal depths for the best-determined aftershocks were between 1.5 and 4.5 km. The aftershock sequence was situated about 2–3 km from two wastewater injection wells that had been injecting 16,000 m^3/mo or more since 2006–2007 at depths of about 1.9 km. A search of records at station NATX in Nacogdoches (about 35 km distant) revealed that several small earthquakes, apparently from the same focus, had occurred in 2008, 2010, and 2011 (Frohlich *et al.*, 2014), and subsequent reanalysis of Transportable Array data revealed additional earthquakes that occurred between 2010 and 2012 (Walter *et al.*, 2016). Fan *et al.* (2016) simulated the spatial and temporal evolution of the pore pressure and stress fields in this region using a coupled finite-element geomechan-



▲ **Figure 12.** (Top) Earthquakes and injection wells in the 2012–2013 Timpson sequence. Circles are earthquakes, triangles are temporary seismic stations, and squares are injection disposal wells. White circles were epicenters for earthquakes occurring prior to installation of temporary network, including the 17 May 2012 M_w 4.8 event. Light gray circles are epicenters determined when the network was partially installed; dark gray circles are the best-located hypocenters occurring after installation of all eight stations. Note that the best-located events form a planar group extending from about 1.5–4.5 km depth (see cross section A–A′; bottom), coinciding with a mapped fault (dark line near B–B′ on map) and situated within 1–3 km of "south" and "north" wells, injecting at ~1.8 km depth. Prior to the 2012 mainshock, injection rates at the north well were ~16,000 m^3/mo; at the south well they were ~24,000–48,000 m^3/mo. Figures reproduced from Frohlich *et al.* (2014).

ical model and concluded that it was plausible that injection induced this earthquake sequence.

Even in the absence of the modeling, the sequence occurrence along a mapped fault, the focal depths of the events, and the proximity, timing, and volume of the injection all support the conclusion that this sequence was almost certainly induced.

Azle, 2013–2015: Almost Certainly Induced

Beginning in November 2013, a series of earthquakes occurred near the city of Azle, about 25 km northwest of Fort Worth. As of 2015, the sequence includes eight earthquakes having magnitudes of 3 or greater; the two largest were m_{bLg} 3.6 events occurring on 20 November 2013 and 8 December 2013. Like other Fort Worth basin event sequences, there was no history of prior seismic activity. Scientists at SMU and the U.S. Geological Survey (USGS) deployed a temporary seismograph network and were able to accurately locate 283 events occurring between December 2013 and April 2014 (Figs. 6 and 13) (Hornbach *et al.*, 2015). The seismicity occurred at depths between 1.5 and 8 km on two steeply dipping, conjugate faults consistent with the general strike of the Newark East fault zone, a mapped fault system that extends northeast–southwest across the seismically active region. Focal mechanisms were consistent with normal faulting.

There are two wastewater injection wells and multiple production wells within 3 km of the seismic activity. Between June 2009 and 2014, injection was ongoing at the closest disposal well at depths of about 2.5 km and rates of 30,000–80,000 m^3/mo. Two gas- and brine-producing wells of interest were situated directly above the earthquake activity, but specific monthly production volumes of brines were not available. Geomechanical modeling of pore-pressure diffusion (Hornbach *et al.*, 2015) indicated that the combination of brine production and wastewater injection was sufficient to generate subsurface pressure changes that could induce earthquakes on near-critically stressed faults.

Because of the absence of historical seismicity prior to injection, the proximity of the injection wells, the relatively high volumes injected compared with other regional wells, the timing of high injection rates with felt seismicity, and the depths of earthquakes at and below the depth of injection, we conclude this sequence is almost certainly induced.

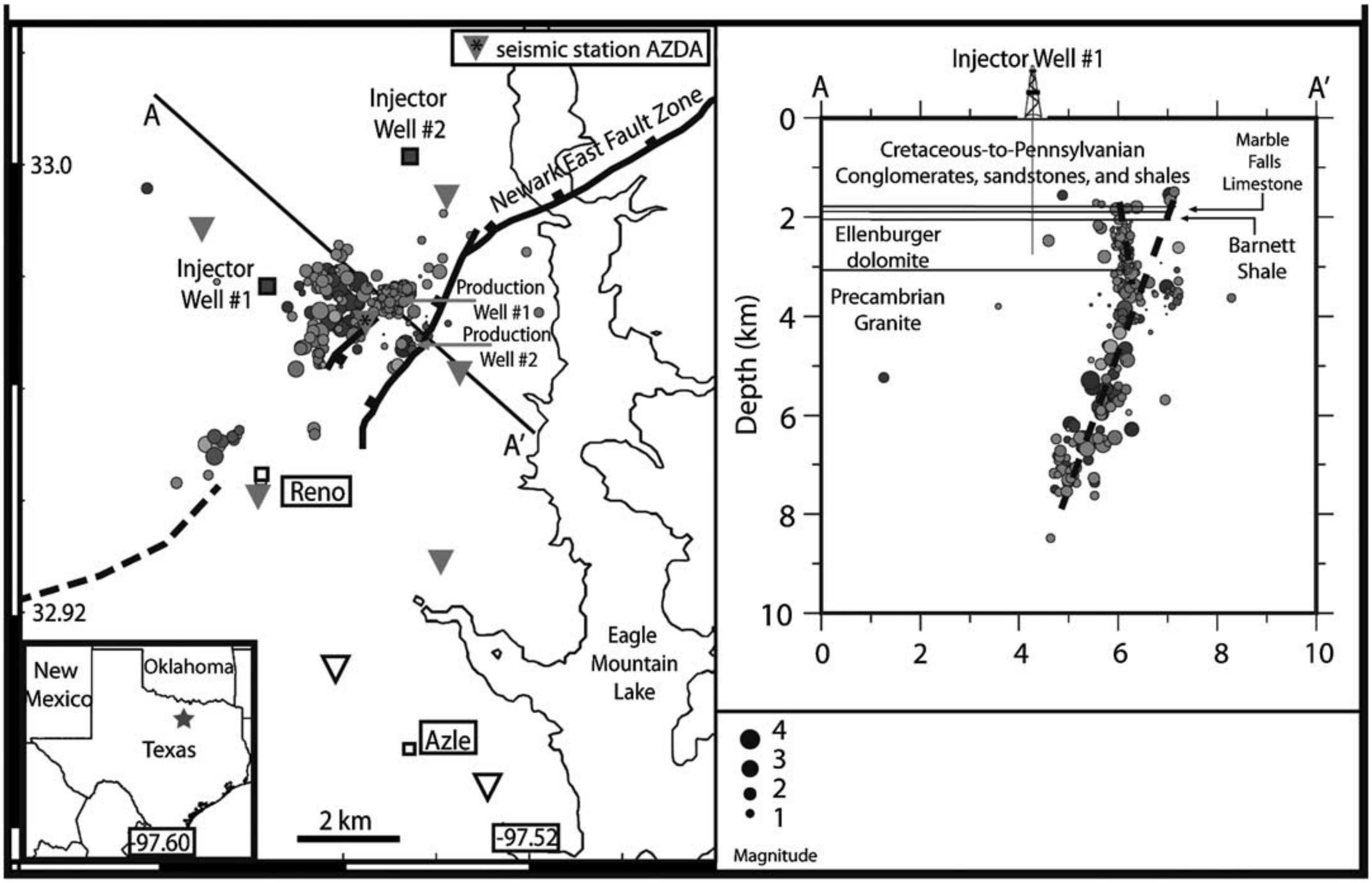
Elsewhere in Northeast Texas. Frohlich (2012) analyzed data collected between November 2009 and September 2011 by the EarthScope Transportable Array and located 67 earthquakes. All of the more-accurately located events were grouped in eight distinct locations, and each of these groups was situated within 3.2 km of one or more injection disposal wells having maximum injection rates of 24,000 m^3/mo or more. Two of these groups (DFW and Cleburne) are among those discussed above. Because of the proximity to high-volume injection wells and the absence of regional historical seismicity, earthquakes in the remaining six groups are probably induced.

The most numerous of the eight groups had 32 earthquakes and was situated in northeastern Johnson County near Venus, about 40 km southeast of Fort Worth and 30 km northeast of Cleburne. This focus has continued to be seismically active up into 2015, including an m_{bLg} 4.0 earthquake on 7 May 2015. To further investigate this activity, scientists at SMU and The University of Texas at Austin have installed several temporary seismograph stations. A focal mechanism for this 2015 earthquake indicates normal faulting (Ⓔ Table S3 and Fig. S1).

West Texas

Snyder, 1974–1982: Almost Certainly Induced

Two sequences of earthquake activity have occurred in association with the Cogdell Field, about 20 km north of Snyder. The

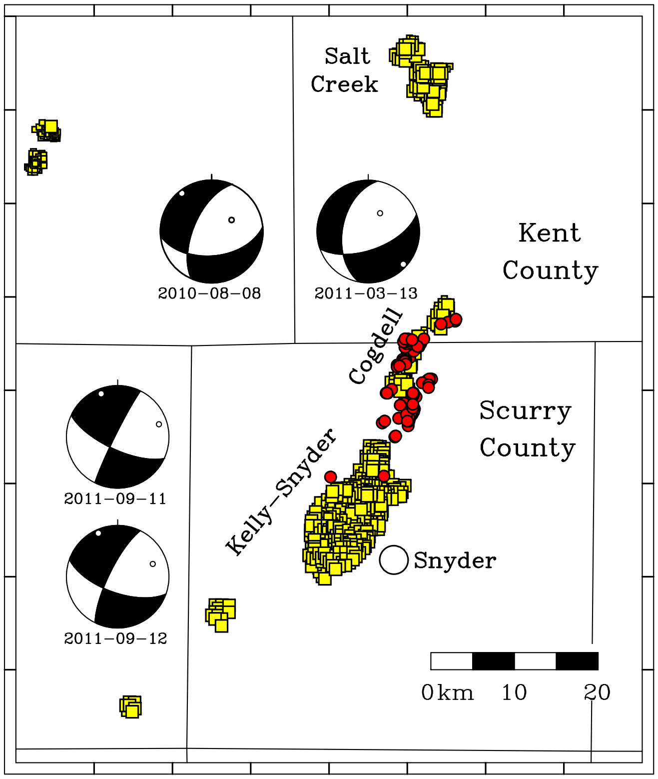


▲ **Figure 13.** Earthquakes near Azle and regional geologic structure. The line labeled AA′ on the map on the left left shows the location of the cross section on the right right. Circles are earthquake epicenters, triangles are temporary seismograph stations, and the star in the inset indicates the map location of the site. Figure revised from Hornbach *et al.* (2015).

first began in 1974 and lasted until 1982; the largest earthquake, with magnitude m_b 4.6, occurred on 16 June 1978. The field began producing in 1949, and waterflooding of the producing reservoir began in April 1956. The injection began at the edges of the field and migrated inward over time; the injection rates increased and exceeded more than 300, 000 m^3/mo by November 1974, when the first known earthquake occurred. A surface-wave analysis of the 1978 earthquake (Voss and Herrmann, 1980) found normal faulting (Ⓔ Table S3 and Fig. S1) and estimated a depth of 3 km. The USGS operated a temporary seismograph network from February 1979 to August 1981 (Harding, 1981) and recorded 20 locatable earthquakes having mean depths of 1.9 km. Both results are consistent with the injection depth of 2.1 km. Davis and Pennington (1989) investigated this sequence and attributed it to the waterflooding of the Cogdell oil field. They modeled fluid pressures in the field and concluded that the earthquakes occurred at the boundaries of regions having low fluid pressures adjacent to higher pressure regions. We conclude this sequence is almost certainly induced because of the absence of historical earthquakes prior to 1974, the huge and sustained injection volumes, the earthquake depths at about the depth of injection, and the supporting modeling evidence.

Snyder, 2006–2012: Probably Induced

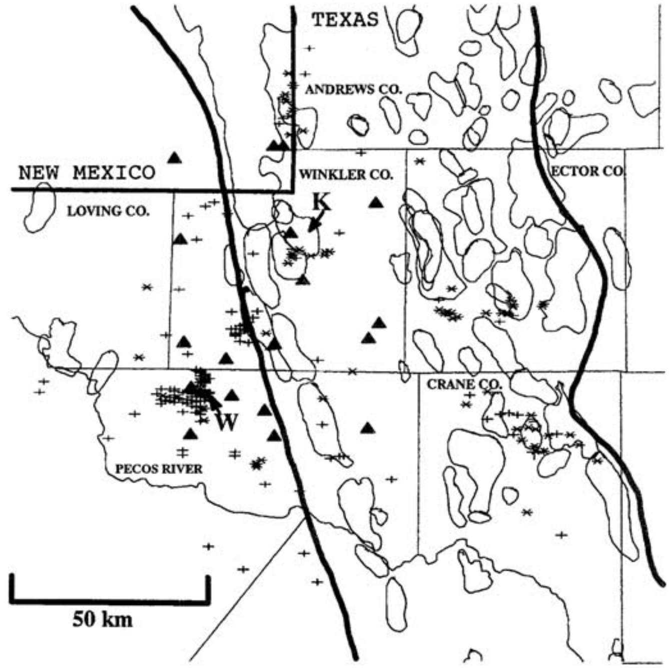
Following more than 20 years with no reported earthquakes, a second sequence of activity in the Cogdell oil field (Figs. 6 and 14) began in 2006; between 2006 and 2015 NEIC reported 24 earthquakes having magnitudes of 3 or greater, including an M_w 4.4 earthquake on 11 September 2011. Four focal mechanisms determined for this sequence included two strike-slip and two normal-faulting events (Fig. 14, Ⓔ Fig. S1, and Table S3). Gan and Frohlich (2013) evaluated EarthScope Transportable Array records to investigate this sequence. They found no evidence that this second sequence was attributable to waterflooding; instead, they found that it coincided with a program to inject supercritical CO_2 in the Cogdell Field. For the Cogdell Field, supercritical CO_2 injection rates averaged about 113 million m^3/mo (volume at standard temperature and pressure) between 2004 and 2012, and there was a temporary increase to more than 225 million m^3/mo in August 2006, just as the first earthquake in the sequence occurred. Although we have no knowledge of mapped regional faults or information about the focal depths of this sequence, we conclude it is probably induced. If so, the M_w 4.4 earthquake is the largest known earthquake induced by injection of supercritical CO_2.



▲ **Figure 14.** Earthquakes 2009–2011 and gas injection wells near Snyder, Texas. Filled circles are earthquakes located by Gan and Frohlich (2013) using data from nearby USArray temporary stations; squares are supercritical CO_2 gas injection wells; and beach balls show reported focal mechanisms for four of the mapped earthquakes. Earthquakes occurring in 1974–1982 in the Cogdell Field have been attributed to waterflooding operations in the Cogdell Field (Davis and Pennington, 1989); however, the 2000–2011 earthquakes mapped here appear to be associated with supercritical CO_2 gas injection (Gan and Frohlich, 2013). Because the history of waterflooding and gas injection is highly similar in the Cogdell, Kelly–Snyder, and Salt Creek Fields, it is presently unclear why earthquakes occur primarily in and near the Cogdell Field. The color version of this figure is available only in the electronic edition.

Permian Basin 1966, Present: Probably Induced

Between December 1975 and September 1979, a 12-station seismograph network was deployed in west Texas to assess seismic risk associated with a proposed nuclear waste disposal site in southeastern New Mexico (Figs. 6 and 15). The network recorded more than 2000 earthquakes, of which about 1300 were located. There were several different investigations analyzing these data (Rogers and Malkiel, 1979; Keller *et al.*, 1987; Doser *et al.*, 1992); all found that much of this seismicity occurred within several active oil and gas fields, notably the War–Wink, Kermit–Keystone, and Apollo–Hendrick Fields. The investigations all concluded the seismicity was probably induced but that more than one mechanism was responsible. For example, some events seemed to be associated with enhanced recovery efforts and others with production.

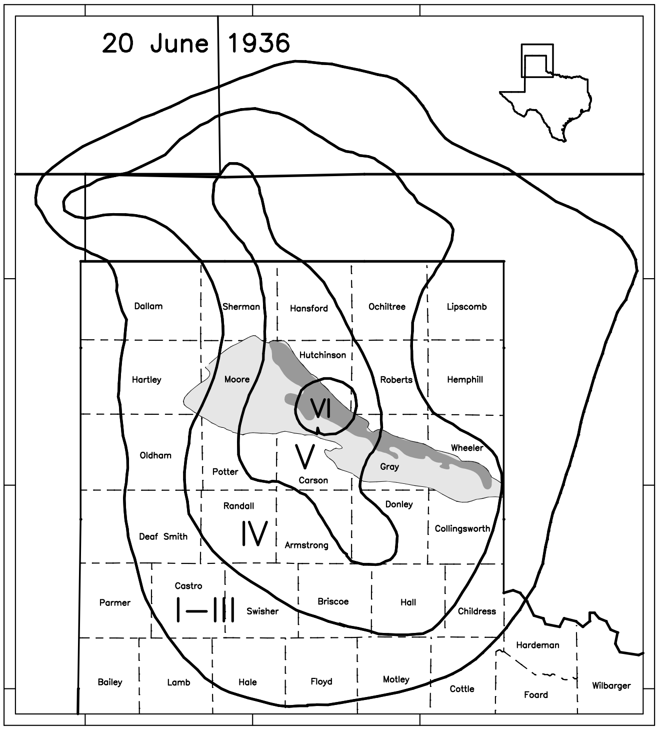


▲ **Figure 15.** Seismicity in 1976–1979 and oil fields of the Permian Basin. The * and + symbols are epicenters relocated using data collected by temporary seismograph stations (triangles) operational from 1976 to 1979; the + symbols are epicenters located with data from fewer than four stations. Oil fields are irregular-shaped regions enclosed by thin lines; bold lines are the boundaries of the Central Basin platform. Several investigators have noted that earthquakes are associated with the Keystone (labeled K) and War–Wink (W) Fields and that seismicity within Crane County and Ector County is generally collocated with oil field outlines. Figure reproduced from Doser *et al.* (1992, p. 483) with permission from de Gruyter Publishers.

Felt earthquakes had not been reported in or near the locations of these petroleum fields prior to 1966; between 1966 and 1978, there have been several reported earthquakes having magnitudes of 3 or greater, including one with M_L 3.9 on 25 January 1976. Because the region was settled much earlier, Rogers and Malkiel (1979) suggest that earthquakes were mostly rare or absent prior to about 1966. Although the relationship between seismicity and petroleum operations appears to be complex, and many active fields there have no earthquakes, we conclude that the majority of Permian basin earthquakes are probably induced.

Texas Panhandle

In Texas, the largest historical earthquakes, other than the 1931 and 1995 west Texas events, occur in the Panhandle, where earthquakes having magnitudes of 5 or greater (as determined from felt areas) have occurred on 20 July 1925 (magnitude of 5.4), 20 June 1936 (magnitude of 5.0), and 12 March 1948 (magnitude of 5.2) (Frohlich and Davis, 2002). Of these, the 1948 earthquake was centered in the northwest corner of the Panhandle, where we know of no contemporaneous



▲ **Figure 16.** Petroleum fields and felt intensities for the 20 June 1936 Panhandle earthquake. Dark and light gray shading indicate oil and gas fields, respectively, developed prior to 1936. Roman numerals are areas experiencing the labeled MMIs. Note that the highest-intensity region of the 1936 Panhandle earthquake coincides with the center of the Panhandle Field. Figure reproduced from Frohlich and Davis (2002) with permission from University of Texas Press.

petroleum production. However, for both the 1925 and 1936 earthquakes (Figs. 6 and 16), the region of maximum intensities coincided with the giant Panhandle oil and gas field.

This, along with the observation that no confirmed earthquakes are known in the region prior to 1910, when petroleum was first discovered here, has led to speculation that Panhandle earthquakes are induced (Pratt, 1926; Frohlich and Davis, 2002). Although the assertion would be credible for the 1936 earthquake (more than 50×10^6 m^3 of oil were produced from the Panhandle Field prior to 1938), it is less plausible in 1925, because vigorous petroleum production was just getting underway then. Moreover, prior to 1910, the population of the Panhandle was scant, and earthquakes occurring then might have gone unnoticed. No information is currently available concerning the focal depths of Panhandle earthquakes, and epicentral locations are not very accurate.

Nevertheless, many of the Panhandle earthquakes in Ⓔ Tables S1 and S2 occurred near active production or injection operations. Although it is possible some Panhandle earthquakes are induced, at present there is insufficient evidence to conclude an induced cause is probable. However, in the analysis of Weingarten *et al.* (2015), some Panhandle events do qualify as earthquakes "associated" with injection. Clearly, more research concerning Panhandle earthquakes is warranted.

DISCUSSION AND CONCLUSIONS

Induced Earthquakes Across Texas Through Time

Earthquakes induced by human activity occur in several different areas of Texas (Fig. 5); and, for some events, the evidence they are induced is exceptionally strong. This is particularly true for three recent sequences of earthquakes associated with wastewater disposal in deep wells. These are the DFW International Airport sequence of 2008–2013 (Frohlich *et al.*, 2011), the Timpson sequence surrounding the M_w 4.8 earthquake of 17 May 2012 (Frohlich *et al.*, 2014), and the Azle sequence beginning in 2013 (Hornbach *et al.*, 2015). All three sequences occurred in regions where prior seismic activity was unknown; all three had accurately determined epicenters situated within about 2 km of active injection wells with maximum monthly injection rates of 24,000 m^3 or greater; all three sequences had accurately determined hypocenters with focal depths at approximately the depth of injection and at greater depths; and epicenters for all three sequences occurred within a few kilometers of known mapped subsurface faults.

Induced earthquakes are not just a recent phenomenon in Texas. The evidence that petroleum operations induced earthquakes in 1925 (Goose Creek) and 1932 (Mexia–Wortham) is credible, in spite of the fact that no seismographs recorded these events. In both cases, careful field investigations (Pratt and Johnson, 1926; Sellards, 1933) established the presence of surface cracks, and in Mexia a pattern of felt reports suggested the source was shallow and coincident with the area where high-volume extraction was underway. The geologists who performed these field investigations, Wallace E. Pratt and Elias H. Sellards, were established and well-respected scientists with strong ties to industry: Pratt was employed by Humble Oil and was among the founders of the American Association of Petroleum Geologists, and Sellards was Director of the Texas Bureau of Economic Geology. Both made statements in academic publications suggesting the earthquakes were caused by petroleum extraction: Pratt and Johnson (1926, p. 590) noted the earthquakes accompanied land subsidence and concluded that this was "directly caused by extraction of oil, water, gas, and sand from beneath the surface." Sellards (1933, p. 111) noted that "the tremor may have been caused by adjustment of the land surface incident to the operations in the oil fields" and, to support this, presented calculations indicating that cumulative production in the fields was 60×10^6–100×10^6 m^3 of oil and water and 20×10^6 m^3 of gas. Their statements suggesting an induced cause for the Goose Creek and Mexia–Wortham earthquakes are notable, especially because induced earthquakes were virtually unknown at that time.

In spite of the long and geographically widespread association between seismicity and petroleum operations (Figs. 5 and 6), some Texas organizations have been slow to acknowledge that induced earthquakes occur in Texas. These include the Texas Railroad Commission, the state agency responsible for regulating operations associated with petroleum production (i.e., drilling and the extraction and injection of petroleum, water, and gas). In 2014, a candidate for election (subsequently elected) to the Texas Railroad Commission was quoted in the media as stating, "When you consider the volume of the earth that is affected in a disposal well and the pressures that we are talking about, it seems highly unlikely that these are having a direct impact on seismic activity" (Barer, 2014). And in 2015, D. Craig Pearson, an earthquake seismologist employed by the Texas Railroad Commission stated that there was "no substantial proof" that induced earthquakes have occurred in Texas (Kuchment, 2015). In comparison with Texas, Oklahoma's petroleum regulatory agency, the Oklahoma Corporation Commission, has been relatively aggressive in responding to induced earthquake concerns. Beginning in 2013, they implemented a traffic-light system to manage review of injection well permits and permitted volumes, and subsequently in selected areas they have issued directives to reduce injection volumes and/or plug hundreds of wells and to limit injection depths.

Induced Earthquakes in Texas Have Multiple Causes

Mechanisms other than wastewater injection appear to be responsible for several Texas earthquake sequences. These mechanisms include fluid extraction for the 1932 Mexia–Wortham earthquake and the 2011 M_w 4.8 earthquake near Fashing (Pennington *et al.*, 1986; Frohlich and Brunt, 2013); near-surface subsidence associated with fluid extraction (Goose Creek); enhanced oil recovery (the 1978 Snyder earthquake m_{bLg} 4.6; Davis and Pennington, 1989); and supercritical CO_2 injection (the 2011 Snyder earthquake M_w 4.3; Gan and Frohlich, 2013).

Indeed, over the past century in Texas, the apparent causes of induced earthquakes have changed as the technologies used to extract petroleum have evolved. Prior to 1940, most fields in Texas produced from relatively shallow strata, were in the primary recovery phase, and often were managed to produce oil as quickly as possible. The resulting removal of large volumes often led to changes in subsurface stress conditions, surface and/or subsurface faulting and cracking, and (sometimes) earthquakes. The 1925 Goose Creek and 1932 Mexia–Wortham earthquakes are prime examples.

As subsurface pressures declined in some of the larger fields, operators realized that waterflooding was necessary to maintain production (secondary recovery). This process began as early as 1938 in the East Texas Field and was in widespread use across Texas when it was initiated in 1956 in the Cogdell Field near Snyder. Davis and Pennington (1989) argue that waterflooding was responsible for the 16 June 1978 Snyder earthquake sequence. For the 1957 Gladewater earthquake, waterflooding of the East Texas Field may have contributed to its occurrence; however, an alternate cause is redistribution of subsurface stress, which is a plausible mechanism, considering the huge volumes of petroleum produced here from strata at depths of 1–2 km.

Like the East Texas Field, many other fields in Texas have long and complex production histories, sometimes making it difficult to assign a single cause to the associated earthquakes. Examples of such fields are in the Permian basin, where numerous fields were discovered in the 1920s, subsequently produced large volumes of petroleum from different strata, and over the decades have undergone various episodes of secondary and tertiary recovery. New shale-play fields, typically in basinal settings not collocated with the older fields, today are undergoing vigorous hydrofracturing operations. Other fields with long and various production histories and earthquakes include the Stratton Field (and the 1997 and 2010 Alice earthquakes) along the Gulf Coast and the Fashing Field (and its earthquakes 1974–2011) south of San Antonio; in both cases, the earthquakes are almost certainly induced, but the complex history makes it difficult to isolate one causal mechanism.

In contrast, the evidence indicates that a single cause—wastewater injection that activates nearby subsurface faults—is primarily responsible for many induced Texas earthquake sequences occurring since 2008. These include the 2008–2013 DFW International Airport sequence, the 2009–2010 Cleburne sequence, the 2012 Timpson sequence, and the 2013–2015 Azle sequence. There also appear to be several other persistent loci of seismic activity associated with injection disposal wells elsewhere in northeast Texas (Frohlich, 2012). However, if we compare the seismicity in northeast Texas and Oklahoma, the Texas seismicity tends to be clustered around a small number of distinct sites, whereas in Oklahoma the associated seismicity is aerially more extensive and distributed geographically over a much larger area (Walsh and Zoback, 2015). There are also considerably fewer Texas earthquakes having magnitudes of 3 or greater. The difference may occur because the injection in northeast Texas is mostly to dispose of fluids produced following hydrofracturing operations, and the seismicity is concentrated around a few wells having higher rates of injection (Frohlich, 2012). In contrast, in Oklahoma much of the disposal is from large volumes of water coproduced during conventional oil production and subsequently reinjected into deeper sedimentary formations that appear to be in hydraulic communication with crystalline basement (Walsh and Zoback, 2015). In Oklahoma, the overpressuring and associated seismicity appears to extend over entire formations, rather than just around individual wells.

Although the Texas data support the assertion that when earthquakes occur, they often are situated within a few kilometers of high-rate injection wells or near fields where large volumes of oil and gas have been produced over many years from relatively shallow strata, the converse is not true. That is, the majority of high-rate disposal wells and highly productive petroleum fields are not associated with nearby earthquakes. Nevertheless, it is important to emphasize that although association is not causation, we cannot dismiss the correlations in time and space over a long operational history, reported at multiple sites, and noted in numerous peer-reviewed publications. At present, it is still poorly understood why seismicity occurs in some environments and not in other apparently similar situations. For Texas, we anticipate that this understanding will improve over time as the Texas seismograph network improves and more seismic data are collected and as future research efforts target areas like the Panhandle and the Permian basin that have been seismically active and where considerable information is available about regional geology.

Although Texas provides examples of earthquakes associated with extraction, secondary recovery, and wastewater injection, at present there have been no reported examples where hydrofracturing operations themselves directly caused felt earthquakes or earthquakes with magnitudes of 3 or greater, such as have been observed in Alberta, British Columbia, Ohio, Oklahoma, and elsewhere (Holland, 2011; Eaton and Mahani, 2015; Farahbod *et al.*, 2015; Skoumal *et al.*, 2015). However, this is unsurprising, considering that earthquakes associated with hydrofracturing are usually small-magnitude events and that seismic station coverage in Texas is relatively sparse.

Similarly, we are unaware of any reservoir-induced earthquakes in Texas (i.e., earthquakes associated with the filling of surface-water impoundments). This is unsurprising, considering that nearly all such earthquakes occur beneath reservoirs having maximum depths of 50 m or more (Gupta, 2002). Only two reservoirs in Texas have depths exceeding 50 m (Lake Travis at 65 m and Lake Amistad at 60 m), and neither have nearby earthquakes.

The Five-Question Test to Assess Evidence for Induced Earthquakes

To assess whether an earthquake is induced or natural, it would be desirable to apply strictly objective criteria relying solely on statistics such as epicenter-to-well distances, comparisons of injection depths and hypocentral focal depths, and production and extraction volumes. For example, for mid-continent U.S. earthquakes between 1973 and 2014, Weingarten *et al.* (2015) classify epicenters reported within a 15-km radius as associated with an injection well and show that associated earthquakes are responsible for the increase in seismic activity observed since 2009.

However, the application of strictly objective criteria has its limitations, especially over century-long intervals in areas like Texas, where there were few seismograph stations, epicentral locations are highly uncertain, focal depths are (mostly) unknown, and the existence and quality of information about extraction and injection changes through time. For example, Hough and Page (2015) attempt to apply objective criteria to evaluate seismicity in Oklahoma: one conclusion they reach is that the 1952 El Reno, Oklahoma, earthquake may have been induced by wastewater injection. But they acknowledge that reported epicenters for the event vary by as much as 30 km, the focal depth is unknown, and rates and volumes injected are unknown. Although applying objective criteria is desirable for areas and time periods when accurate location and injection/extraction data are available, we concluded that a subjective approach was more reasonable for assessing the Texas historical catalog. Even in mid-continent United States from 1973 to 2014, as evaluated by Weingarten *et al.* (2015), we suspect that location errors were likely to be 15 km or more for a large fraction of epicenters, especially those occurring prior to 2000.

For our subjective question-based test (Appendix), different individuals, after considering the observations, are likely to answer the questions differently. However, individuals seldom disagree on the answers to all five questions. Thus, the value of the question-based approach is that even when there is disagreement, it serves to focus discussion on the critical aspects of the evidence. This is more productive than the arguments that arise from simply attempting to categorize earthquakes as induced or not induced. Undoubtedly, some readers would assign different scores than this article's authors did in Ⓔ Table S2. This is entirely appropriate, and we invite others to perform this exercise. For readers desiring to further evaluate historical Texas earthquakes, we provide the information in Ⓔ Tables S1 and S2 in a plain-text version as Table S4.

Also, as noted above, the scoring (and the locations) of catalogued earthquakes are subject to change in response to future research. For example, for earthquakes in west Texas and the Panhandle, the scores might change if more detailed information becomes available concerning regional faulting, focal depths, or regional injection and production practices. The analysis of earthquakes occurring near Irving and Dallas, Texas, since 2014 is not yet complete, so question QP concerning publication receives a score of 0.0. Furthermore, questions QT and QS (time and space) receive scores of 0.5 because there was a production well (now shut-in) near the epicenters; these scores may change to either 1.0 or 0.0 if ongoing analysis determines whether or not it is plausible this well induced seismic activity.

DATA AND RESOURCES

We assembled the historical catalog of Texas earthquakes occurring in 1847–2015 with reported magnitudes of 3 and greater (Ⓔ Tables S1 and S4) by merging events reported by Frohlich and Davis (2002), the International Seismological Centre (ISC), and the National Earthquake Information Center (NEIC). The historical catalog changes with time, not only because new events occur and are added to the catalog, but also in response to information resulting from ongoing research efforts. For example, whereas Frohlich and Davis (2002) and several earlier sources mention an earthquake reported "at the Centerville Powerhouse Camp" near Chico, Texas, occurring 20 March 1950, it now seems likely that this report described an event near the Centerville Powerhouse in Chico, California (we have been unable to identify a Centerville Powerhouse in Texas). The 1950 location in Texas is now characterized as possibly spurious in the catalog.

For this and previous studies of Texas earthquakes, we obtained information concerning well locations, permitting history, and monthly volumes of oil, gas, and water, both injected and extracted, primarily from IHS, Inc., a private company that organizes information provided by the Texas Railroad Commission. In Texas, the Railroad Commission (which no longer has any authority over railroads) is the agency responsible for regulating all petroleum activity and archiving this information. The Railroad Commission's database is publicly available online and includes monthly injection information for individual wells and leases, which is generally complete for the past 20–30 years. Our information for fields prior to that time was from various published reports.

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APPENDIX

FIVE QUESTIONS TO ASSESS HOW STRONGLY THE EVIDENCE SUGGESTS AN EARTHQUAKE IS INDUCED

QT. *Timing:* In this location, are earthquakes of this character known to begin only after the commencement of nearby petroleum production or fluid injection operations that could induce seismic activity?

QS. *Spatial correlation:* Are the epicenters spatially correlated with such production or injection operations (i.e., within 5 km for well-determined epicenters or within 15 km otherwise)?

QD. *Depth:* Is information available concerning focal depths of earthquakes at this location, and does this suggest some depths are shallow, probably occurring at or near production or injection depths?

QF. *Faulting:* Near production or injection operations, are there mapped faults or linear groups of epicenters that appear to lie along a fault? Here, "near" is within 5 km if the earthquake or earthquake sequence of interest has well-determined epicenters, or within 15 km otherwise.

QP. *Published analysis:* Is there a credible published paper or papers linking the seismicity to production or injection operations?

For each earthquake and each question QT, QS, QD, QF, and QP, answer "Yes," "Possibly," or "No" and then score as follows:

- +1.0 if answer is "Yes";
- +0.5 if answer is "Possibly";
- +0.0 if answer is "No".

Then, to assess how likely it is the earthquake is induced, sum the scores.

- If sum = 0.0–1.0, then earthquake is tectonic (T).
- If sum = 1.5–2.0, then earthquake is possibly induced (PsI).
- If sum = 2.5–3.5, then earthquake is probably induced (PrI).
- If sum = 4.0–5.0, then earthquake is almost certainly induced (ACI).

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