Final Technical Report

# INDUCED OR TRIGGERED EARTHQUAKES IN TEXAS: ASSESSMENT OF CURRENT KNOWLEDGE AND SUGGESTIONS FOR FUTURE RESEARCH

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Recipients name: University of Texas at Austin
Office of Sponsored Proejcts
Austin, TX 78713-7726

Principal Investigator: Cliff Frohlich
Institute for Geophysics
10100 Burnet Road (R2200)
University of Texas at Austin
Austin, TX 78758-4445
cliff@ig.utexas.edu

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Cliff Frohlich (P.I.) Institute for Geophysics, 10100 Burnet Road (R2200), University of Texas at Austin, Austin, TX 78758-4445; tel. 512-471-0460, cliff@ig.utexas.edu

## TECHNICAL ABSTRACT

This project systematically evaluates historical earthquake activity in Texas, compilations of oil and gas fields, and Class II injection disposal wells. Although the principal objective is to assess which earthquakes are caused by human activities, statistically it is more robust to identify quakes that occur in or near active petroleum fields or injection wells, i.e., "quakes in close with human enterprise" (QUICHE), regardless of whether it can be established unequivocally that they are human-caused. For compilations of petroleum fields the project relies on the atlases published in 1983 and 1989 by the Texas Bureau of Economic Geology; for injection disposal wells the project uses publicly available data archived by the Texas Railroad Commission. This report considers earthquakes occurring between 1847 and 2012 having reported magnitudes of M3.0 and greater in four geographic regions within Texas—West Texas, the Texas Panhandle, the Texas Gulf Coast, and Northeast Texas. In all four geographic regions the report identifies both natural and QUICHE events. The two largest earthquakes in Texas history, with M ~6.0 occurred in West Texas; both are of natural origin; however, numerous earthquakes in the Permian Basin have occurred near/within petroleum fields; earthquakes occurring since 1974 near Snyder in the Cogdell field where injection for secondary recovery has been ongoing since the 1950's. In the Texas Panhandle no earthquake activity has been definitely established prior to the development of petroleum fields beginning in the 1910's; however, population was very sparse prior to that time. Nevertheless, more than 70 per cent of all reported earthquakes in the Panhandle, including the largest-magnitude events, occur within or near petroleum fields. In the Gulf Coast region, earthquakes south of San Antonio and west of Corpus Christi occur within or on the boundary of active petroleum fields; this includes the largest-magnitude events; however, earthquakes occurring elsewhere are of natural origin, including seven reported prior to 1920. In Northeast Texas the two largest-magnitude earthquakes are QUICHE events, as are all earthquakes reported since 2000. Thus, in Texas as a whole, nearly two-thirds of all historical earthquakes occur in/near petroleum fields; this fraction is five-sixths for earthquakes occurring since 2000. Several future research projects have the potential to improve our understanding of the relationship between seismicity and human activities in Texas; these include: (1) a systematic analysis of EarthScope USArray seismic data collected in Texas to identify/locate small earthquakes and assess their relationship with petroleum fields and injection wells; (2) evaluating the focal depths of historical Panhandle earthquakes to determine whether it is plausible they are human-caused; (3) systematically compiling and updating subsurface faulting information and petroleum field properties for the state of Texas; (4) collecting and assembling into a data base historical data archived in microfiche form by the Texas Railroad Commission, describing injection disposal well properties; (5) adding additional three-component continuously-operating seismograph stations in Texas.

## NON-TECHNICAL ABSTRACT

This project assesses the relationship between locations of historical Texas earthquakes, petroleum fields, and injection disposal wells, e.g., wells used to dispose of flowback fluids

from hydrofracturing operations. Nearly two-thirds of all Texas earthquakes have occurred in/near petroleum fields or near injection disposal wells; this suggests many Texas earthquakes might be human-caused. This report suggests several research projects that would help us better understand when human activity triggers seismic activity in Texas, and how to mitigate/control this phenomenon.

## 1. INTRODUCTION

### 1.1 Purpose and Scope

This research program evaluates historical and recent seismicity in Texas, identifying earthquakes that may have been induced or triggered by human activity related to injection or petroleum production. The ultimate objective of this study is to understand why human activity may cause earthquakes in some locations and not in others. However, the immediate objective is to identify geographic regions, individual oil and gas fields, or particular seismic sequences appropriate for more intensive study, and to assess what will be required to obtain and analyze the data for each.

Where data is readily available, this project will organize these data and from this, determine to what extent clear links exist between oil and gas production activities and seismicity. However, in other cases the relevant data is disorganized or is proprietary. Thus a second important objective of this study is to evaluate what might be done to access these data, and will propose several future research projects that could further elucidate the relationship between seismic and human activities in Texas.

Texas, with its long and various history of petroleum production, and with both natural and induced earthquakes, provides a natural laboratory for analyzing where induced earthquakes do and don't occur. Several different regions of Texas have experienced intensive oil and gas production activities that have been ongoing since the 1920's, i.e., nearly a century. Natural earthquakes are relatively rare, and thus when earthquakes occur in close geographic association with human activities, attribution of causation is more plausible than in regions where natural earthquakes are common.

Induced or triggered seismicity has not previously been studied systematically across Texas; the Texas populace is generally not risk averse and historically is highly supportive of activities related to petroleum production. Indeed, from the perspective of many Texans, the occurrence of earthquakes in Texas is rare, concern about them is an annoyance, and the most serious risk they pose is that recording small earthquakes or calling too much attention to them might lead to excessive regulation. The Texas Railroad Commission records information concerning more than 100,000 producing oil and gas wells, and tens of thousands of injection wells, and yet there are probably fewer than 20 fields where induced earthquakes may occur.

### 1.2 PUBLICATIONS RESULTING FROM WORK PERFORMED

*Published:*

Frohlich, C. (2012). A two-year survey comparing earthquake activity and injection well locations in the Barnett Shale, Texas, *Proceedings of the National Academy of Sciences*, **109**, 13934-13938, doi:10.1073/pnsas.1207728109.

Frohlich, C. (2012). A survey of earthquakes and injection well locations in the Barnett Shale, Texas, *The Leading Edge*, **31**, 1446-1451.

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?

*Bulletin of the Seismological Society of America* **102** 457-466, doi:10.1785/0120110179.

## 1.3 BACKGROUND: INDUCED/TRIGGERED EARTHQUAKES IN TEXAS

In the mid-twentieth century earthquake seismologists recognized that earthquakes could be associated with human activities such as the filling of reservoirs (Carder, 1945), the injection of fluids into the subsurface (Evans, 1966), and the extraction of fluids, such as water, oil, or gas. There is now a considerable literature on this (for reviews, see Nicholson and Wesson, 1990; Suckale, 2009; 2010).

However, in Texas there was speculation (and controversy) about this association even earlier. For example, after the M5.4 Texas Panhandle earthquake of 30 July 1925, Pratt (1926) stated:

> "There is also a general impression that the earthquake may have been caused by the oil field operations. No evidence supporting [this] was established... Certainly there is no reason to suspect that the removal of oil contributed to the forces which caused the earthquake."

However, following the Wortham-Mexia M4.0 earthquake of 9 April 1932, Sellards (1933) noted:

> "…the fact that the tremor 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. That adjustments of level may occur under these conditions is known from the history of the Goose Creek oil field in Harris County, Texas, where subsidence of three or more feet has occurred."

Between 1975 and 1995, investigations concerning earthquakes in three separate geographic locations in Texas concluded it was highly likely or at least plausible that earthquakes in these locations were induced or triggered by human activity:

- *Eagle Ford* – Residents of the towns of Fashing, Pleasanton and Karnes City, small towns 60-100 km south of San Antonio, began experiencing small earthquakes in 1973. Production in the Imogene field (near Pleasanton) had begun in 1944; in the Fashing field production began in 1958. Pennington et al. (1986) analysed these earthquakes and noted that fluid pressures in the Fashing field had dropped to ~20 percent of its original value. They concluded that the earthquakes might be caused by differential compaction or because depressurization affected friction on previously creeping faults. Subsequently on 9 April 1993 an apparently similar M4.3 earthquake occurred near Fashing (Davis et al., 1995).

  On 20 October 2011 a larger, M4.8 earthquake occurred near Fashing. Its possible origins are complicated by the fact that the Eagle Ford Shale is now undergoing extensive hydrofracturing operations, and there are injection disposal wells within a few km of the NEIC-reported epicenter.

• *Snyder* – In 1974 a sequence of earthquakes began near Snyder, Texas, apparently associated with the Cogdell oil field (Davis and Pennington, 1989). The Cogdell field had been undergoing waterflooding (injection to enhance secondary recovery) since 1956. This was a massive operation, involving injection of up to $4x10^6$ $m^3$ of water a year at more than 100 wells spaced at intervals of about 0.5 km on a grid. An M4.6 earthquake occurred on 16 June 1978. Both injection and seismic activity has continued up to the present; an M4.3 Snyder earthquake occurred on 11 September 2012. Davis and Pennington (1989) modeled subsurface fluid pressures and concluded that earthquakes seemed to occur where fluid pressure gradients were highest, but that absolute fluid pressures may have high enough to induce failure along locked faults.

• *Permian Basin, West Texas* – A seismic network of ~12 stations operating in the Permian Basin near Kermit, Texas between 1975 and 1979 was able to locate ~1300 microearthquakes. Rogers and Malkiel (1979), Keller et al. (1987) and Doser et al. (1992) analyzed these data and all concluded that many earthquakes seemed to be associated with enhanced recovery operations, especially in the War Wink, Kermit and Keystone oil fields. However, the relationship isn't simple, as earthquakes didn't occur in all fields undergoing waterflooding, and earthquakes reportedly may have occurred in some fields prior to production.

In 2002, Frohlich and Davis published their book, *Texas Earthquakes*, which thoroughly reviewed available information about seismicity in Texas up through the year 2000. The present investigation updates their book for earthquakes occurring through September 2012, but also has a different focus, i.e., the present investigation specifically assesses whether individual earthquakes are clearly of natural origin, or alternatively possibly induced/triggered by human activity. Although *Texas Earthquakes* discusses this issue for several earthquakes, it does not assess this systematically for all earthquakes, as in this report. To my knowledge, this report is the first investigation to systematically evaluate a statewide catalog of Texas earthquakes to assess whether they were induced/triggered.

Since 2008, there has been renewed interest in induced or triggered earthquakes because of concern that small earthquakes may be caused by the exploitation of unconventional gas shales. This development has been made possible by technological innovations such as horizontal drilling and improved hydrofracturing methods that have been widely applied in Texas since about 2000. These innovations make it possible to produce gas cheaply from strata having low natural permeability, even in developed areas where previously it wasn't feasible to drill wells. This has led to an enormous development boom in the Barnett Shale of north Texas (Montgomery et al. , 2005), the Haynesville Shale of east Texas, and the Eagle Ford Shale of central Texas. It has caused a huge increase in the number and volume of injection wells in Texas. This is because after a well has undergone hydrofracturing, much of the hydrofracturing fluid returns to the surface along with natural gas during the production phase; also, in some overpressured formations natural subsurface water may return to the surface. In both cases these are wastes that require disposal, often by injection into deep permeable strata.

Subsequently there has been research published concerning two Texas locations where earthquakes may have been induced or triggered by the injection of hydrofracture wastes:

• *Dallas-Fort Worth* - Between 30 October 2008 and May 2009 a sequence of small earthquakes ($m_b \leq 3.3$) were widely felt in parts Dallas-Fort Worth, Texas (Frohlich et al. , 2010; 2011). After the sequence began, scientists from Southern Methodist University installed a six-station temporary local network and obtained high-quality 3-component records for aftershocks occurring between 20 November and 1 December 2011. Analysis of these data demonstrated that the events originated from a focus on the Dallas-Fort Worth Airport, less than 0.5 km from a injection well completed in August 2008 that extends to a depth of 4.2 km, drilled to dispose of hyrofracture flowback fluids associated with the production of natural gas. Precise locations of the aftershocks indicated they occurred along a ~ 1 km NNE-SSW trend, with a preferred focal depth of ~4.4 km. This trend is approximately coincident with that of a mapped normal fault in the subsurface, and consistent with the maximum horizontal in situ stress direction. Because of the absence of previous historical earthquakes, the proximity of the injection well, and the observation that earthquakes began only six weeks after injection commenced, it is highly likely that fluid injection triggered the 2008-2009 sequence.

• *Cleburne, Texas* – On 9 June 2009, an M2.8 earthquake occurred near Cleburne, Texas, about 50 km south of Fort Worth. Once again scientists at Southern Methodist University deployed a temporary seismic network, and this network detected 38 locatable earthquakes occurring between June 2009 and June 2010 (Howe et al., 2010; Howe, 2012). The earthquakes were distributed along a north-northwest trend approximately 2 km in length, with an average depth of 3.55 km. This location was about 1.3 km from a injection disposal well that had commenced injecting in October 2007, and 3.2 km distant from a second injection well that had commenced injecting in September 2005. Focal mechanisms determined for the best-recorded events indicated the earthquakes occurred along a NNE or SSW trending normal fault with a dip of ~50°. This is consistent with observations quaternary NNE trending extensional faults that are prevalent across parts of Texas, Oklahoma, Louisiana, and Arkansas. The proximity of the Cleburne earthquakes to injection wells, and the observation that no previous local earthquakes were known in the area, suggests it is plausible they were associated with injection.

In a scenario similar to those Pratt (1926) described following the 1925 Panhandle earthquake, some members of the public and some media stories have expressed concern that 'drilling' and 'fracking' may be causing earthquakes. The presently available research finds no evidence that drilling causes earthquakes; in Texas there have been no investigations reporting earthquakes with magnitudes exceeding M2.0 associated with hydrofracturing (however, see Kanamori and Haukkson, 1993; de Pater and Baisch, 2011; Holland, 2011; and BC Oil and Gas Commission (2012) describing hydrofracturing-associated earthquakes in locations outside of Texas). Instead, the recent earthquakes in the Barnett Shale appear to be associated with injection wells.

Finally, on 25 April 2010, an M3.9 earthquake occurred near Alice, Texas, a community about 75 km west of Corpus Christi. Analysis of felt reports and seismograms recorded at nearby USArray stations indicated it had a shallow focal depth, probably 3.0 km or less, with an epicenter coincident with the boundary of the Stratton oil field (Frohlich et al., 2012). The Stratton field lies along the Vicksburg Fault Zone, and has produced about 3 trillion cubic feet of natural gas and 100 million barrels of oil since production commenced in 1938. Although the earthquake occurred during an era when production in the Stratton field has declined, it is possible it is triggered by extraction of oil and gas, given the absence of previous nearby natural seismicity, the huge volumes of petroleum produced, and its location at the boundary of the Stratton field.

### 1.4 Approach

*Geographical organization:* To evaluate Texas seismicity I have organized this project geographically (Figure 1). Sections of this report focus on earthquakes in West Texas (section 4.1), the Texas Panhandle (section 4.2), the Gulf Coast (section 4.3), and northeast Texas (section 4.4). Within each region I assess the origins of individual earthquakes and/or groups of similar earthquakes.

*Categorizing individual earthquakes:* Although it is desirable to assess whether human activity induces or triggers earthquakes; for any individual earthquake it is usually impossible to prove that human action caused the event. For fluid injection, we know many earthquakes occur that are not near injection wells, and many injection wells don't seem to generate earthquakes, thus the single occurrence of an earthquake near a well is not proof of cause[1]. Even when scientists agree concerning all observations concerning the geographic proximity of earthquakes and wells, and the relative timing of injection and seismic activity, they may not agree concerning whether human actions had any influence.

For example, for the Dallas-Fort Worth sequence of 2008-2009, Janska and Eisner (2012) remain unconvinced that the Dallas-Fort Worth earthquakes of 2008-2009 were triggered, in spite of facts that (Frohlich et al., 2012):

- There had been no previously reported seismicity before the sequence began in 2008;
- The sequence occurred within a km of an injection well and near the depth of injection; and
- Injection at the well began only six weeks before the seismicity began.

Thus in the present study, I will categorize earthquakes as <u>quakes in close with human enterprise</u> (QUICHE) if they occur in or near active oil and gas fields or near active injection wells. Identifying QUICHE events is statistically advantageous because it is robust—there is seldom doubt about whether or not earthquake is near an active field or well—and it avoids fruitless argument. Moreover, when seismicity occurs in close association with human activity, scientific analysis, public policy, and regulation may be called for regardless of whether human cause can be established unequivocally.

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[1] The situation is analogous to the controversy a half-century ago concerning whether or not smoking causes lung cancer: we can't prove cause for an individual case because some nonsmokers get cancer and many smokers do not; however, a controlled comparison of populations of smokers and nonsmokers allows one to estimate how many cancer cases are attributable to smoking.

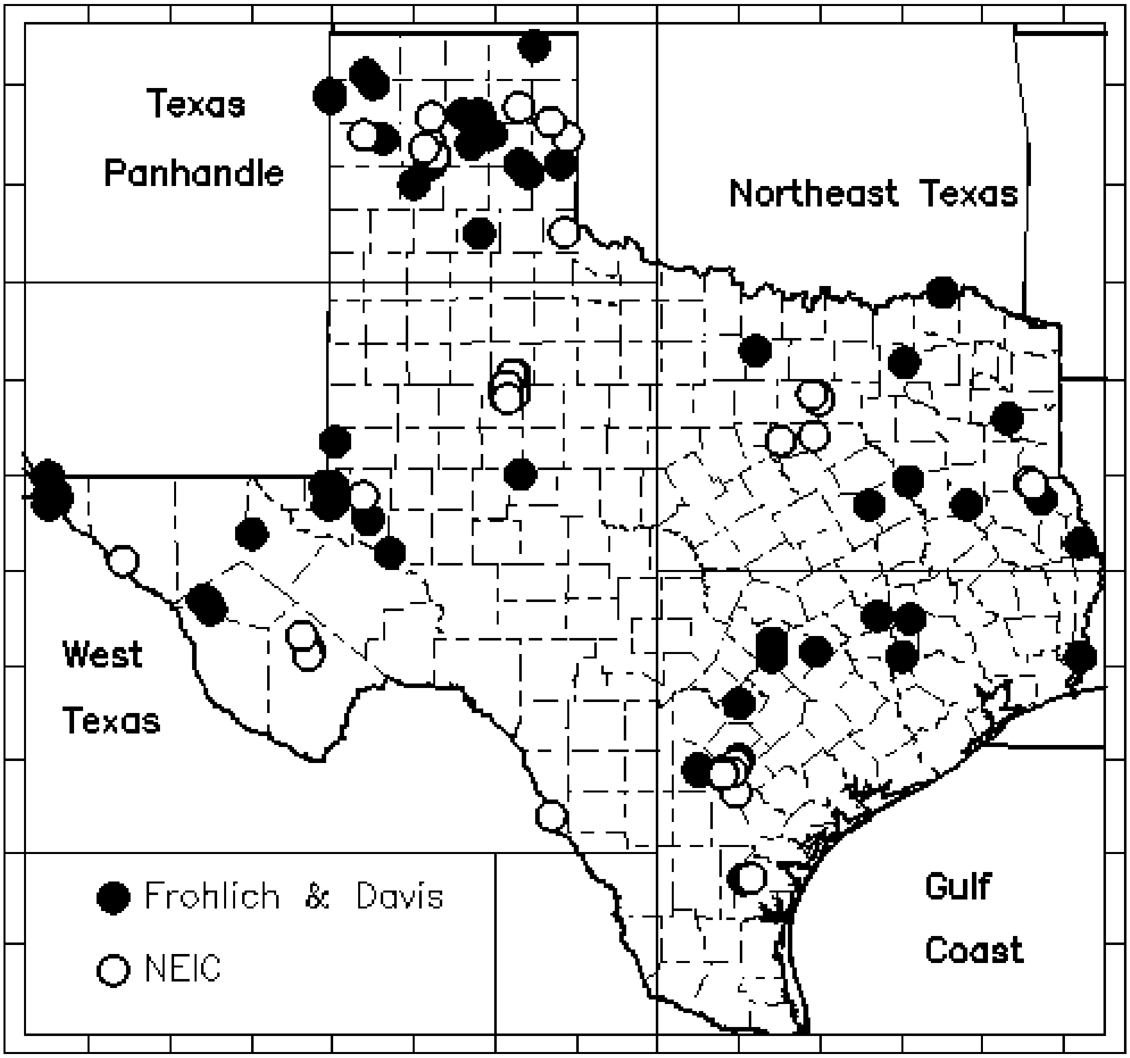


**Figure 1.** Earthquakes in Texas with magnitudes of 3 or greater. Filled circles are events occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC. Thick lines are regional boundaries of the four regions discussed in this report: WT – west Texas; GC – Gulf Coast; TP – Texas Panhandle; NET - northeast Texas.

Thus each earthquake will be assigned to the following categories:

- *natural (tectonic)* [N]: The epicenter or epicentral group is more than 10 km distant from human activities that might induced/trigger seismicity, or it occurred prior to when such activities commenced.

- *closely associated with a producing oil or gas field* [P]: The reported epicenter or epicentral group is within 10 km of an active or formerly active oil and gas field.

- *closely associated with an injection well* [I]: The reported epicenter or epicentral group is within 10 km of an active or formerly active injection well.

A few catalogued events are possibly spurious [S], e.g., they are known only from newspaper reports, or there is evidence that misunderstandings, transcription errors, or other blunders are responsible for their inclusion in a catalog, i.e., they may not have been earthquakes at all.

## 2. DATA

### 2.1 Seismicity Data

For earthquakes occurring prior to 2000, this project will utilize the catalog of Texas earthquakes having M3 or greater compiled by Frohlich and Davis (2002) as Table 9.3 in their book, *Texas Earthquakes* (see Figure 1). This includes earthquakes occurring in both the 19th and 20th centuries, and during the compilation some care was taken for older events to evaluate the credibility of the report as an earthquake, the preferred location, and the assigned magnitude.

For earthquakes occurring in 2001 and subsequently, this project will utilize locations reported by the National Earthquake Information Center (NEIC), sometimes augmenting these with locations reported by the International Seismological Centre (ISC). Also, in some cases earthquakes reported by these agencies have been relocated by this report's author. In this report, all tables of epicenters will specify the origin of the location listed.

**Table 1**. Abbreviations used in this report.

API – American Petroleum Institute

BEG – University of Texas Bureau of Economic Geology

CF – Cliff Frohlich (used to identify non-catalog locations determined by Frohlich)

DPC – Davis, Pennington and Carlson (1989)

FD – Frohlich and Davis (2002)

GC – Gulf Coast

ISC – International Seismological Centre

NEIC – National Earthquake Information Centre

NET – Northeast Texas

PDE – NEIC *Preliminary Determination of Epicenters*

PH – Texas Panhandle

RRC – Texas Railroad Commission

USGS – U.S. Geological Survey

WT – west Texas

## 2.2 Oil and Gas Field Data, and Injection Well Data

The Texas State Legislature founded the Texas Railroad Commission (RRC) in 1991 to regulate railroads in Texas, but since 1919 the Commission has also regulated the production of oil and gas. In 1984 the RRC ceased its role in the economic regulation of railroads, and by 2005 it ceased to have any regulatory authority for any aspect whatsoever of the railroad industry.

However, the RRC continues to be responsible for regulating most activities related to the production of oil and gas in Texas, including issuing permits for drilling wells and recording information about volumes of oil and gas produced. By law petroleum producers are also required to provide the RRC with certain information concerning fluid injection, both when it used to stimulate production and also when it used to dispose of wastes such as hydrofracture fluids. Information about production and injection at individual wells is publicly available; however, for activities prior to about 1990 much of the information is only available on microfiche.

In Texas the number of wells drilled since 1919 for oil and gas purposes is prodigious, on the order of a million, too many to consider individually, especially since most RRC data prior to 1990 isn't digital. Fortunately, between 1980 and 1990 the Texas Bureau of Economic Geology (BEG) undertook studies summarizing the properties of Texas oil and gas wells (Figure 2), publishing the *Atlas of Major Texas Oil Reservoirs* (Galloway et al., 1983; and updated subsequently) and the *Atlas of Major Texas Gas Reservoirs* (Kosters et al. , 1989, and updated subsequently). Following standard industry practice, when a large group of wells were drilled to access a particular petroleum source, the group is called a 'field' and the BEG studies reported statistics for fields rather than for individual wells.

For this study I use the mapped locations and summary statistics for oil and gas fields provided by the BEG publications (i.e., Galloway et al. , 1983; Kosters et al. , 1989) as the basis for comparisons with seismicity data prior to about 1995. Although the statistical features summaries are somewhat out-of-date, most of the oil and gas fields they describe are still active.

I also augment this with maps of Texas oil and gas fields compiled by Geomap Company[2]. For this project the most useful maps are the Executive Reference Map series, which summarizes oil and gas fields and mapped faults on maps with scale 1:380,000. Geomap sells maps to the petroleum industry. However, it considers the information on the maps proprietary and doesn't allow users to reproduce the mapped information, nor does it provide citations for the origin of information concerning mapped faults. However, their maps are somewhat more current and than the Ewing (1990), Galloway et al. (1983) and Kosters et al. (1989) maps .

[2] See http://www.geomap.com/georef.html

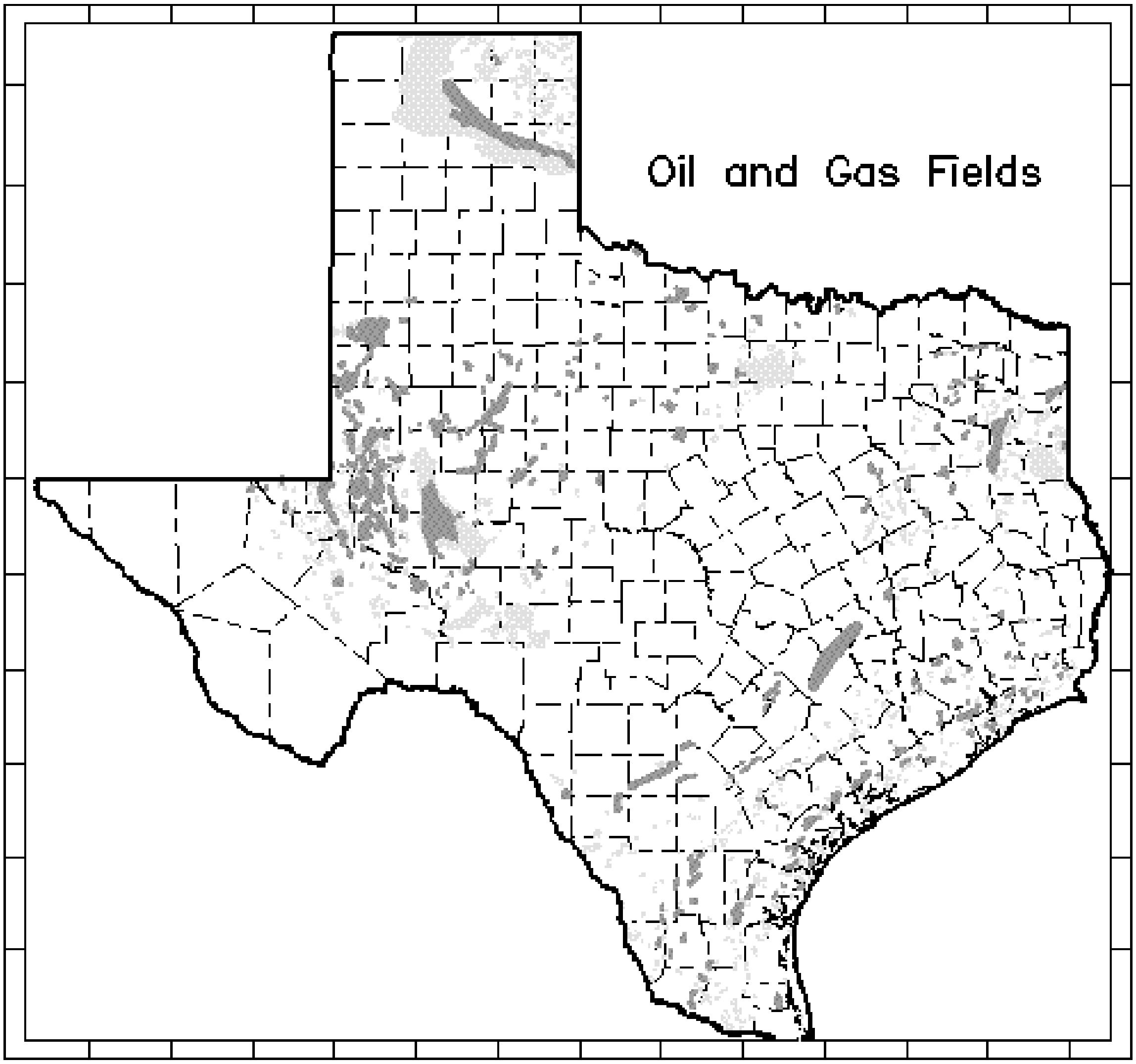


**Figure 2.** Oil and gas fields of Texas. Darker shaded areas are oil fields from Galloway et al. (1983); lighter shaded areas are gas fields from Kosters et al. (1989).

Information concerning individual injection wells active since about 1990 is available on the Commission's website (see http://www.rrc.state.tx.us/data) and the completeness and availability of more recent information is improving with time. In Texas most of the development of unconventional gas shales using hydrofracturing has occurred since 2004; for this interval injection well information is available online and presumably complete (Figure 3). For this study I obtained locations of all Class II injection wells in the RRC database. Several commercial organizations supply information obtained from the RRC database to subscribers; for this project I obtained some of the information from a company called IHS.

## 3. RESULTS BY GEOGRAPHIC REGION

### 3.1 West Texas (WT)

*Alpine (natural)* – The 14 April 1995 earthquake near Alpine had magnitude $M_W$ 5.7, placing it (with the 1931 Valentine earthquake) as one of the two largest historical earthquake in Texas (Frohlich and Davis, 2002). It was accompanied by numerous aftershocks and sporadic activity has continued, with an M3.6 earthquake reported by the NEIC in January 2012. The Alpine earthquakes are of natural origin; there are no nearby petroleum fields or injection wells.

*Delaware Basin (near a producing field?)* – This 1 August 1975 earthquake wasn't very well recorded, but its NEIC-reported location places it within the Delaware Basin where there are numerous oil and gas fields. The location of this earthquake is uncertain; thus its relationship to petroleum fields is uncertain.

*Eagle Pass (near an injection disposal well)* - This 3 April 2005 M3.5 earthquake was felt in Eagle Pass, a Texas community along the Rio Grand Valley. There are a number of injection wells within ~30 km of its reported epicenter in Maverick County; e.g., one with relatively high volumes (API# 42127304890000) has been active steadily since 1983 with monthly injection rates of 20,000-100,000 BWPM.

*El Paso (natural)* – Earthquakes have been reported felt in El Paso since 1889. I found no evidence that there have been nearby petroleum fields or injection wells. El Paso has been occupied since the 17th century when Spanish missions were established, and it is conceivable that a future analysis of mission records might uncover reports of natural earthquakes occurring prior to 1880 (e.g., see Perez, 2001).

*Permian Basin (near producing fields)* – As discussed in Section 1.3, petroleum development began in the Permian Basin in the 1920's and at least since 1965 earthquakes have been reported in several different locations (see Doser et al., 1992).

*Rattlesnake Canyon (near producing fields)* – This 2 January 1992 M5.0 earthquake was situated along the Texas-New Mexico border near producing oil fields.

*Silver (near producing fields)* – The 30 January 1986 M3.3 Silver earthquake occurred within/near or near producing oil fields.

*Snyder (near injection wells)* – Historically, probably the most active seismic center in Texas is associated with the Cogdell Field near Snyder, Texas (see Section 1.3). The field began producing in the 1950's, involving massive waterflood operations that have been underway since the mid-1950's. Earthquakes were first noticed in 1974; an M4.6 earthquake occurred in 1978 (see Davis and Pennington, 1989); activity has continued since, including an M4.3 on 11 September 2011.

*Valentine (natural)* – The 16 August 1931 M6.0 Valentine earthquake is (with the 1995 Alpine earthquake) the largest historical Texas earthquake. And like the 1995 earthquake, the Valentine activity is of natural origin.

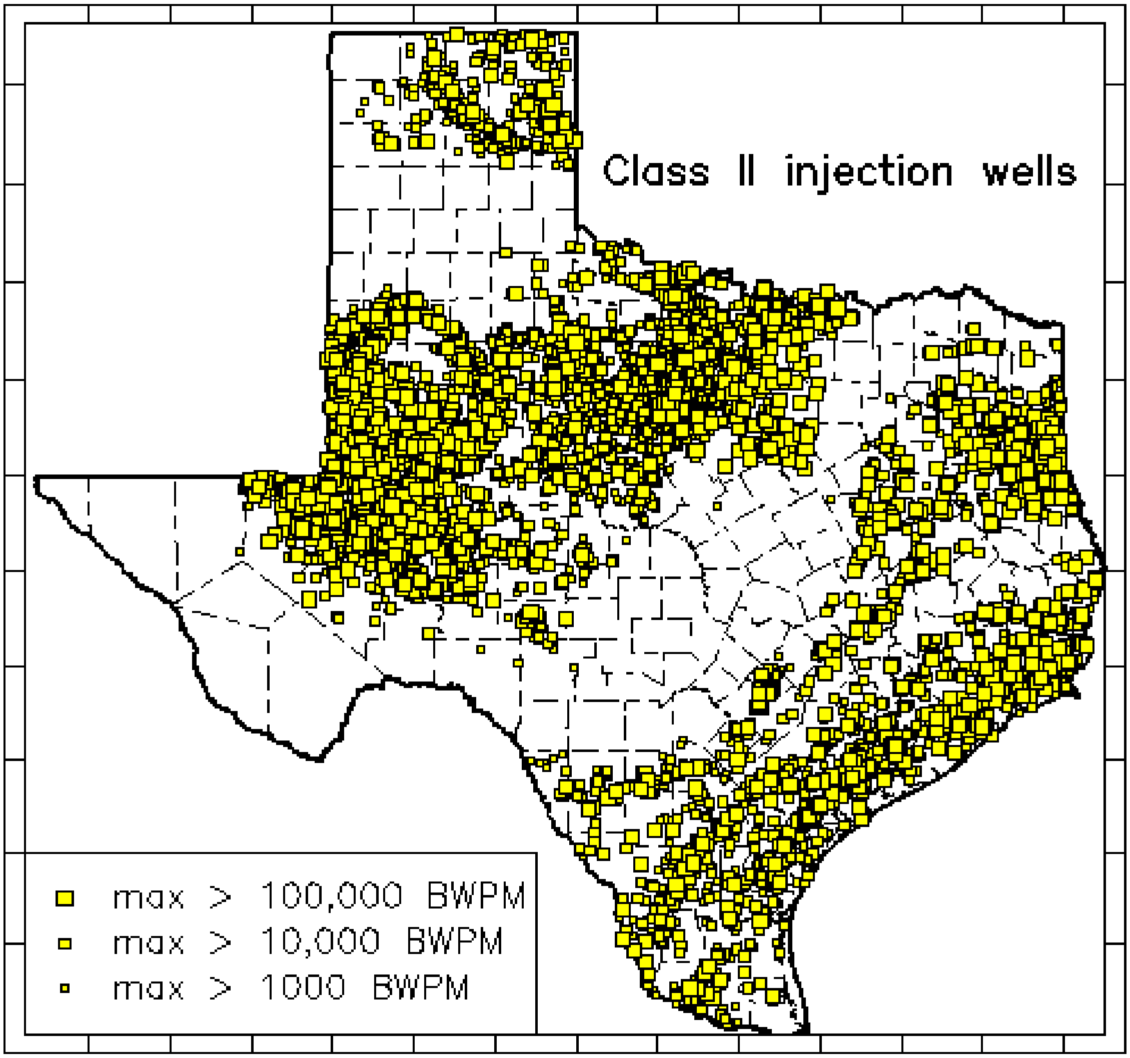


**Figure 3.** Class II injection wells in Texas. Large, intermediate, and small symbols are wells with maximum monthly reported rates of > 100,000 BWPM (barrels of water per month), >10,000 BWPM, and >1000 BWPM.

**Table 2.** West Texas (WT) earthquakes. 'Agency' is abbreviation of organization reporting this location (see Table 1); 'cat' is category assigned: N – natural, P – near producing oil or gas field; I – near active injection well; S – possibly spurious report; 'mo' is month of occurrence; 'da' is day of occurrence; 'lat' is reported latitude; 'long' is reported longitude; 'felt' indicates that NEIC reported felt information; 'geolocation' is Texas quadrant and nearby community name: WT – west Texas; PH – Panhandle; GC – Gulf Coast; NET – northeast Texas. Events in italics are fore- or aftershocks, defined as events in a sequence occurring within one month one another; main shock is in bold type.

| *agency* | *cat* | *year* | *mo* | *da* | *time* | *lat* | *long* | *dep* | *magnitude* | *felt* | *geolocation & notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alpine** | | | | | | | | | | | |
| **FD** | **N** | **1995** | **04** | **14** | **003256.2** | **30.280** | **-103.350** | **17** | **5.7 Ms GS** | **6F** | **WT Alpine (many aftershocks** |
| *FD* | *N* | *1998* | *04* | *15* | *103342.4* | *30.190* | *-103.300* | *10* | *3.6 MnGS* | *3F* | *WT Alpine* |
| PDE | N | 2011 | 02 | 17 | 182534.41 | 30.11 | -103.30 | 5 | 3.3 LgGS | ... | WT Alpine |
| PDE | N | 2012 | 01 | 24 | 182102.61 | 30.32 | -103.38 | 5 | 3.6 LgGS | 4F. | WT Alpine |
| **Delaware Basin** | | | | | | | | | | | |
| DPC | P? | 1975 | 8 | 1 | 727 | 31.400 | -104.000 | | 3.0BUSGS | 2F | WT Delaware Basin |
| **Eagle Pass** | | | | | | | | | | | |
| PDE | I | 2005 | 04 | 03 | 143916.97 | 28.39 | -100.31 | 5 | 3.5 LgGS | 4F. | WT Eagle Pass |
| ***El Paso*** | | | | | | | | | | | |
| DPC | N | 1889 | 5 | 31 | 2000 | 32.00 | -106.50 | | 3.6 | 5F | WT El Paso |
| DPC | N | 1923 | 3 | 07 | 0503 | 31.80 | -106.50 | | 4.7 | 6F | WT El Paso |
| DPC | N | 1931 | 10 | 02 | | 31.80 | -106.50 | | 3.2 | 3F | WT El Paso |
| DPC | N | 1936 | 8 | 08 | 0140 | 31.80 | -106.50 | | 3.0 | 3F | WT El Paso |
| DPC | N | 1936 | 10 | 15 | 1800 | 31.80 | -106.50 | | 3.0 | 3F | WT El Paso |
| DPC | N | 1937 | 3 | 31 | 2345 | 31.70 | -106.50 | | 3.0 | 3F | WT El Paso |
| DPC | N | 1969 | 5 | 12 | 826 | 31.80 | -106.40 | | 3.6 | 6F | WT El Paso |
| **DPC** | **N** | **1972** | **12** | **09** | **0558** | **31.75** | **-106.40** | | **3.0** | **3F** | **WT El Paso** |
| *DPC* | *N* | *1972* | *12* | *10* | *1437* | *31.75* | *-106.40* | | *3.0* | *4F* | *WT El Paso* |
| **Permian Basin** | | | | | | | | | | | |
| DPC | P | 1965 | 8 | 30 | 51737.9 | 31.900 | -103.000 | 33 | 3.5BUSCGS | | WT Permian Basin |
| DPC | P | 1966 | 8 | 14 | 152555.0 | 31.900 | -103.000 | 33 | 3.4 | 6F | WT Permian Basin |
| *DPC* | *P* | *1971* | *7* | *30* | *14552.5* | *31.720* | *-103.000* | *10* | *3.0BUSGS* | | *WT Permian Basin* |
| **DPC** | **P** | **1971** | **7** | **31** | **145351.0** | **31.700** | **-103.060** | **10** | **3.4BUSGS** | | **WT Permian Basin** |
| *DPC* | *P* | *1976* | *1* | *19* | *4 328.1* | *31.900* | *-103.090* | *1* | *3.2* | *4F* | *WT Permian Basin* |
| **DPC** | **P** | **1976** | **1** | **25** | **44824.2** | **31.900** | **-103.090** | **2** | **3.9** | **5F** | **WT Permian Basin** |
| DPC | P | 1977 | 4 | 26 | 9 3 5.0 | 31.900 | -103.080 | 4 | 3.3 | 4F | WT Permian Basin |
| DPC | P | 1978 | 3 | 02 | 1004 | 31.550 | -102.560 | | 3.5 | 3F | WT Permian Basin (several foreshocks) |

| *agency* | *cat* | *year* | *mo* | *da* | *time* | *lat* | *long* | *dep* | *magnitude* | *felt* | *geolocation & notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DPC | P | 1982 | 1 | 4 | 165610.4 | 31.200 | -102.300 | 5 | 3.9 | 3F | WT Permian Basin |
| PDE | P | 2001 | 11 | 22 | 000708.02 | 31.79 | -102.63 | 5 | 3.1 LgGS | ... | WT Permian Basin |
| **Rattlesnake Canyon** | | | | | | | | | | | |
| FD | P? | 1992 | 01 | 02 | 114535.6 | 32.360 | -102.970 | 5 | 5.0 MnTUL | 5F | WT Rattlesnake Canyon |
| **Silver** | | | | | | | | | | | |
| FD | P | 1986 | 01 | 30 | 222637.1 | 32.020 | -100.700 | 5 | 3.3 MnGS | 4F | WT Silver |
| **Snyder (Cogdell Field)** | | | | | | | | | | | |
| DPC | I | 1978 | 6 | 16 | 114653.8 | 33.000 | -100.800 | 5 | 4.6BDPC | 5F | WT Snyder |
| DPC | I | 1982 | 11 | 28 | 23648.2 | 32.920 | -100.850 | 5 | 3.3 | 4F | WT Snyder |
| PDE | I | 2008 | 01 | 29 | 102453.24 | 32.90 | -100.84 | 5 | 3.3 LgGS | .F | WT Snyder |
| PDE | I | 2010 | 01 | 27 | 045933.05 | 32.90 | -100.83 | 5 | 3.1 LgGS | .F | WT Snyder |
| PDE | I | 2010 | 08 | 08 | 011238.07 | 32.90 | -100.85 | 5 | 3.4 MwRMT | 2FM | WT Snyder |
| *PDE* | *I* | *2010* | *10* | *09* | *074227.63* | *32.93* | *-100.89* | *5* | *3.1 LgGS* | *..* | *WT Snyder* |
| **PDE** | **I** | **2010** | **10** | **26** | **065629.79** | **32.92** | **-100.85** | **5** | **3.1 LgGS** | **..** | **WT Snyder** |
| *PDE* | *I* | *2011* | *03* | *01* | *033012.76* | *32.88* | *-100.84* | *5* | *3.1 LgGS* | *2F* | *WT Snyder* |
| *PDE* | *I* | *2011* | *03* | *12* | *152200.86* | *32.88* | *-100.90* | *5* | *3.0 LgGS* | *..* | *WT Snyder* |
| **PDE** | **I** | **2011** | **03** | **13** | **201620.62** | **32.99** | **-100.77** | **5** | **3.8 MwRMT** | **2FM** | **WT Snyder** |
| *PDE* | *I* | *2011* | *03* | *14* | *001948.80* | *32.96* | *-100.81* | *5* | *3.0 LgGS* | *..* | *WT Snyder* |
| *PDE* | *I* | *2011* | *03* | *19* | *233401.21* | *32.98* | *-100.77* | *5* | *3.0 LgGS* | *.F* | *WT Snyder* |
| *PDE* | *I* | *2011* | *03* | *28* | *091211.95* | *32.91* | *-100.82* | *5* | *3.0 LgGS* | *..* | *WT Snyder* |
| *PDE* | *I* | *2011* | *04* | *02* | *220514.09* | *33.06* | *-100.76* | *5* | *3.0 LgGS* | *.F* | *WT Snyder* |
| *PDE* | *I* | *2011* | *05* | *02* | *190714.99* | *33.06* | *-100.79* | *5* | *3.2 LgGS* | *.F* | *WT Snyder* |
| **PDE** | **I** | **2011** | **09** | **11** | **122744.32** | **32.85** | **-100.77** | **5** | **4.3 MwRMT** | **4FM** | **WT Snyder** |
| *PDE* | *I* | *2011* | *09* | *12* | *141834.05* | *32.82* | *-100.87* | *7* | *3.4 LgGS* | *3F* | *WT Snyder* |
| *PDE* | *I* | *2011* | *11* | *24* | *231549.01* | *32.94* | *-100.85* | *5* | *3.1 LgGS* | *..* | *WT Snyder* |
| **PDE** | **I** | **2011** | **12** | **09** | **184733.24** | **32.94** | **-100.86** | **5** | **3.5 LgGS** | **3F** | **WT Snyder** |
| *PDE* | *I* | *2011* | *12* | *17* | *144658.46* | *32.81* | *-100.85* | *5* | *3.2 LgGS* | *3F* | *WT Snyder* |
| **Valentine** | | | | | | | | | | | |
| **DPC** | **N** | **1931** | **8** | **16** | **1140** | **30.69** | **-104.57** | | **6.0** | **8F** | **WT Valentine (sequence)** |
| *DPC* | *N* | *1931* | *11* | *03* | *1550* | *30.70* | *-104.60* | | *3.0* | *3F* | *WT Valentine* |
| DPC | N | 1955 | 1 | 27 | 0037 | 30.60 | -104.50 | | 3.3 | 4F | WT Valentine |
| PDE | N | 2010 | 05 | 27 | 2047 | 31.11 | -105.58 | | 3.7 MLGS | | WT NW Valentine |

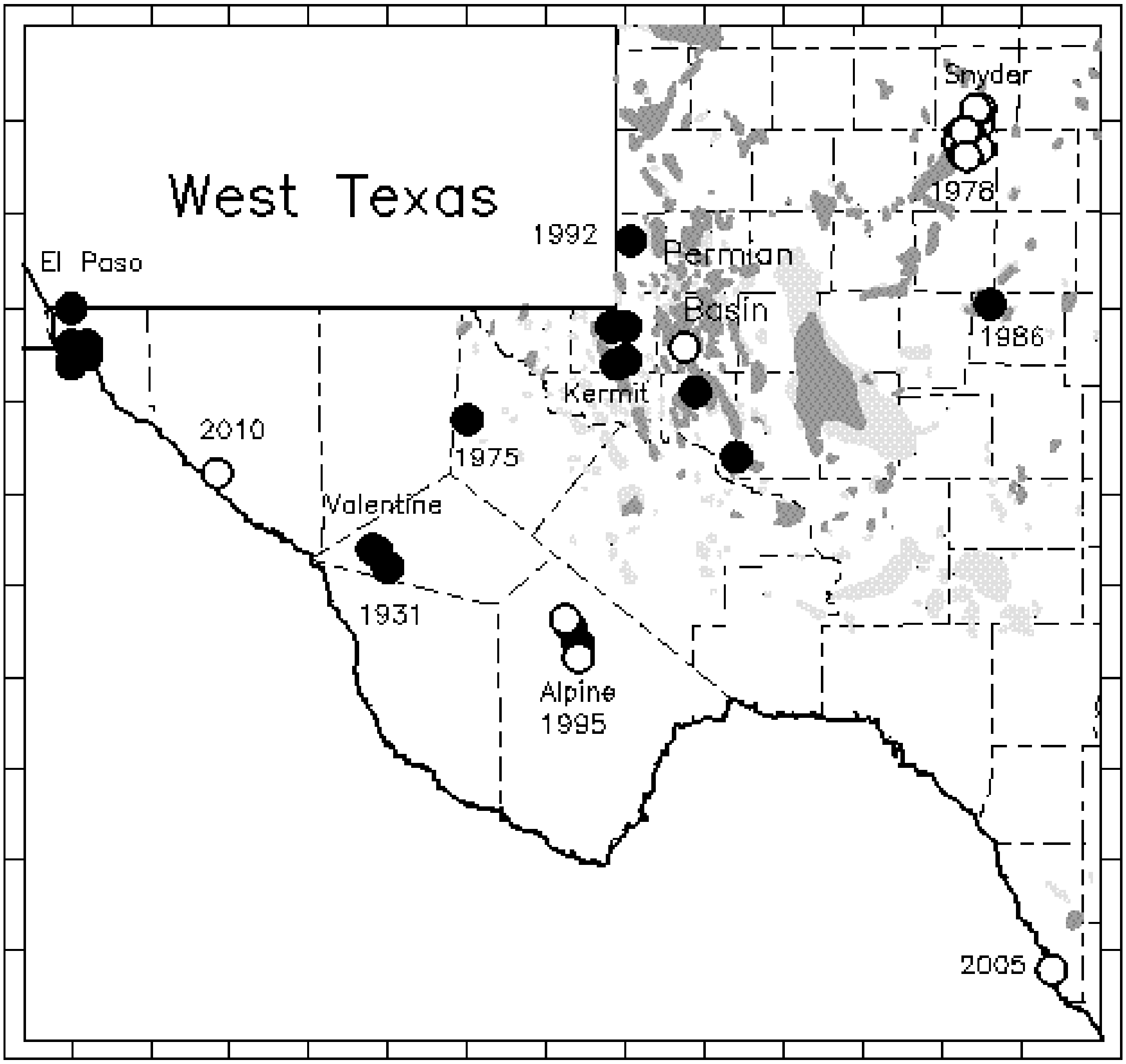


**Figure 4.** Earthquakes and oil and gas field in west Texas. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC; dark shaded areas are oil fields from Galloway et al. (1983); light shaded areas are gas fields from Kosters et al. (1989).

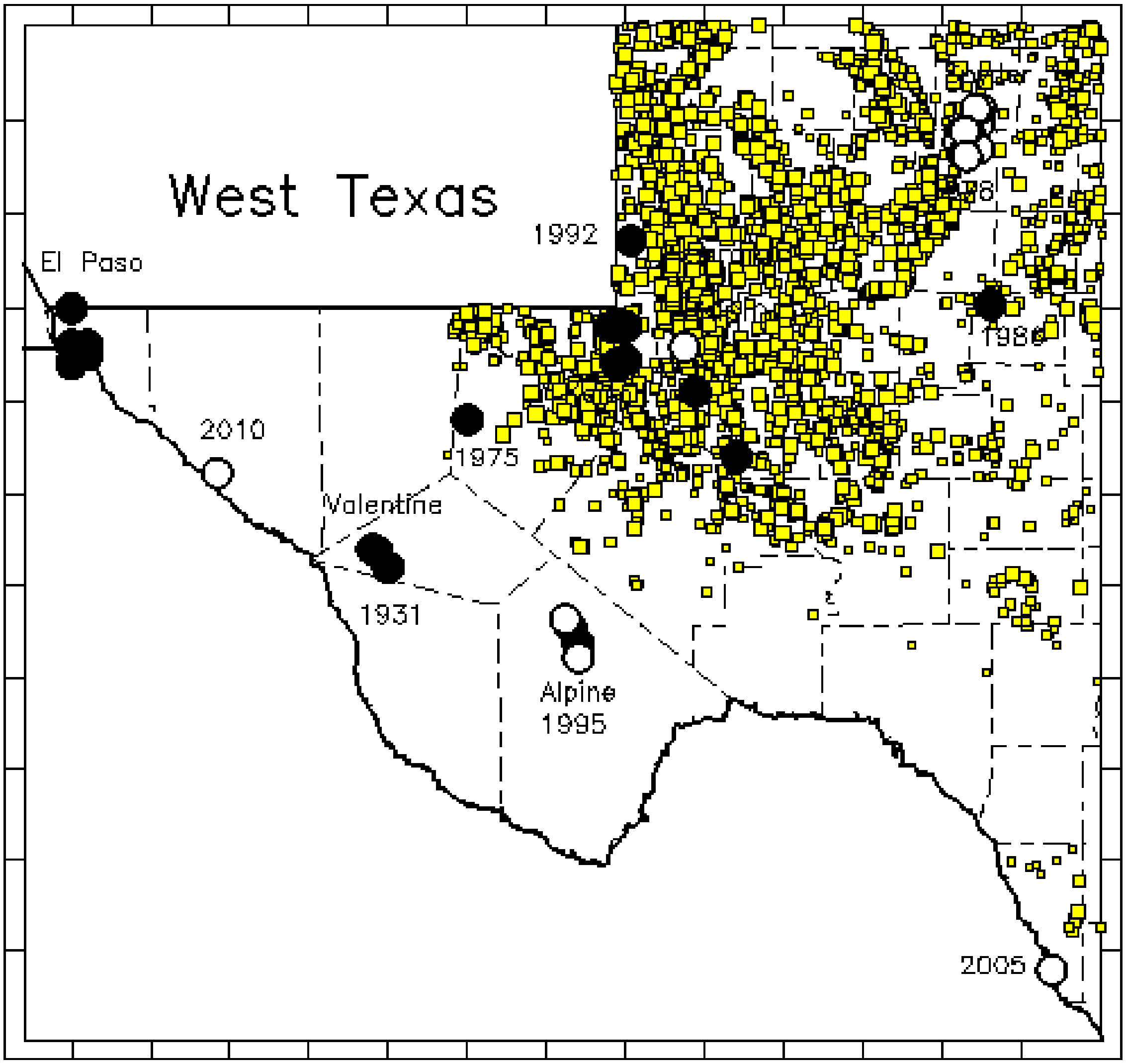


**Figure 5.** Earthquakes and class II injection wells in west Texas. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC. Large, intermediate, and small symbols are wells with maximum monthly reported rates of > 100,000 BWPM (barrels of water per month), >10,000 BWPM, and >1000 BWPM.

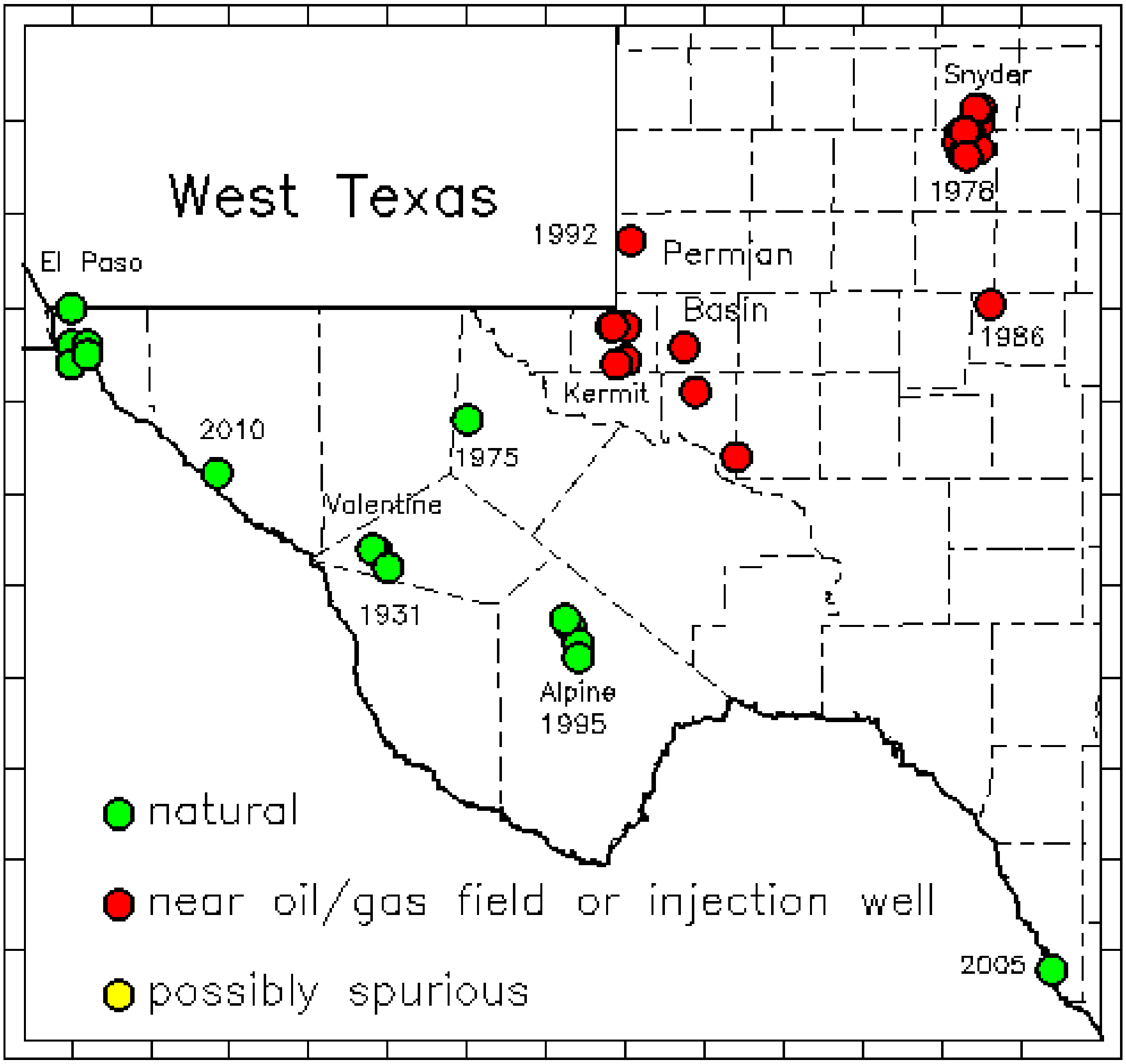


**Figure 6.** Categories assigned in this study to earthquakes in west Texas.

### 3.2 Texas Panhandle (PH)

*Amarillo (most natural; some recent events near injection wells)* – most of the earthquakes with epicenters reported here must be natural, as they are well south of producing fields. However, a high-volume injection disposal well north of Amarillo has been active since 1991 (well API# 42375313470001) and earthquakes occurring in 2003 and later occurred near this well.

*East of Amarillo (near producing fields)* – These earthquakes near Clarendon, Wheeler, and McLean occurred on the edge of the large Panhandle gas field

*Amistad* (natural) – I have found no producing fields or permitted injection wells on the Texas-New Mexico border near this epicenter.

*Dalhart (natural)* - I have found no producing fields or permitted injection wells in the eastern Texas Panhandle near this epicenter. There are permitted injection wells near here today but I am aware of none when these events occurred in 1948 and 1982.

*South of Dalhart (near injection wells)* – Available records indicate there are several injection wells near these 1998 and 2010 epicenters. The highest-volume well (API# 42359301500000) commenced injecting in 1983 and has been active nearly continuously subsequently.

*Panhandle (near producing fields)* - The huge Panhandle field has been producing since before 1920, and earthquakes have occurred here at least since 1925 (the 1917 event may be spurious). None of the publications describing these earthquakes (see Frohlich and Davis, 2002, for a summary) imply that they are induced or triggered. However, it is noteworthy that they occurred in or near producing fields in an area where there are no records of prior seismic activity.

*East-Central Panhandle (one natural earthquake; some near injection wells)* – Except for the 7 October 2007 earthquake, these events all occur near active injection wells. The magnitudes are all ~M3, and thus it is possible their locations are inaccurate.

*Perryton (near producing fields)* – This 1974 earthquake occurred in an area where there are numerous active gas fields.

*Silverton (natural, or possibly spurious)* – As discussed by Frohlich and Davis (2002), this earthquake was reported one day prior to, and 100 km south of, the M5.4 25 July 1925 earthquake. It is possible the initial reports were in error and the event is spurious. The reported location is not near producing fields.

**Table 3.** Texas Panhandle (PH). 'Agency' is abbreviation of organization reporting this location (see Table 1); 'cat' is category assigned: N – natural, P – near producing oil or gas field; I – near active injection well; S – possibly spurious report; 'mo' is month of occurrence; 'da' is day of occurrence; 'lat' is reported latitude; 'long' is reported longitude; 'felt' indicates that NEIC reported felt information; 'geolocation' is Texas quadrant and nearby community name: WT – west Texas; PH – Panhandle; GC – Gulf Coast; NET – northeast Texas. Events in italics are aftershocks, defined as events in a sequence occurring within one month one another; main shock is in bold type.

| *agency* | *cat* | *year* | *mo* | *da* | *time* | *lat* | *long* | *dep* | *magnitude* | *felt* | *geolocation & notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Amarillo** | | | | | | | | | | | |
| DPC | S | 1907 | 4 | 07 | 0000 | 35.200 | -101.800 | | 3.6 | 5F | PH Amarillo |
| DPC | N | 1951 | 6 | 20 | 1837 | 35.000 | -102.000 | | 4.2 | 5F | PH Amarillo |
| *PDE* | *N* | *2000* | *8* | *07* | *171908* | *35.39* | *-101.81* | *5* | *3.3 LgGS* | *.F* | *PH Amarillo* |
| *PDE* | *N* | *2000* | *8* | *07* | *183409* | *35.39* | *-101.81* | *5* | *3.0 LgGS* | *.F* | *PH Amarillo* |
| *PDE* | *N* | *2000* | *8* | *07* | *213621* | *35.39* | *-101.81* | *5* | *3.0 LgGS* | *.F* | *PH Amarillo* |
| *PDE* | *N* | *2000* | *8* | *10* | *133950* | *35.39* | *-101.81* | *5* | *3.0 LgGS* | *.F* | *PH Amarillo* |
| **PDE** | **N** | **2000** | **8** | **17** | **010805.45** | **35.39** | **-101.81** | **5** | **3.9 LgGS** | **.F** | **PH Amarillo** |
| PDE | N | 2000 | 12 | 16 | 220854 | 35.40 | -101.80 | 5 | 3.9 LgGS | .F | PH Amarillo |
| PDE | I | 2003 | 9 | 24 | 150209.09 | 35.28 | -101.74 | 5 | 3.3 LgGS | 4F | PH Amarillo |
| PDE | I | 2006 | 3 | 28 | 235511.49 | 35.36 | -101.87 | 5 | 3.0 MLGS | .F | PH Amarillo |
| PDE | I | 2012 | 8 | 12 | 003605.15 | 35.37 | -101.90 | 5 | 3.3 LgGS | ... | PH Amarillo |
| **E of Amarillo** | | | | | | | | | | | |
| DPC | S | 1936 | 6 | 19 | 2100 | 35.200 | -100.700 | | 3.0 | 3F | PH Clarendon |
| DPC | P | 1982 | 11 | 7 | 00410. | 35.2 | -100.2 | | 3.1 | | PH Wheeler |
| FD | P | 1996 | 11 | 23 | 105418.5 | 35.110 | -100.600 | 5 | 3.0 MnGS | .? | PH McLean (several events) |
| ***Amistad*** | | | | | | | | | | | |
| FD | N | 1993 | 09 | 29 | 020119.1 | 35.900 | -103.030 | 5 | 3.3 MnGS | 3F | PH Amistad |
| FD | N | 1993 | 11 | 30 | 030731.8 | 35.860 | -103.030 | 5 | 3.3 MDSNM | 4F | PH Amistad |
| **Dalhart** | | | | | | | | | | | |
| DPC | N | 1948 | 3 | 12 | 0429 | 36.000 | -102.500 | | 5.2 | 6F | PH Dalhart |
| DPC | N | 1982 | 10 | 14 | 125245.8 | 36.100 | -102.600 | 5 | 3.9 | 3F | PH Dalhart |
| **S of Dalhart** | | | | | | | | | | | |
| PDE | I | 1998 | 04 | 27 | 152246.25 | 35.45 | -102.38 | 5 | 3.2 LgGS | | PH |
| PDE | I | 2010 | 02 | 04 | 094128.12 | 35.49 | -102.62 | 2 | 3.3 MwRMT | .FM | PH W |
| **Panhandle** | | | | | | | | | | | |
| DPC | S | 1917 | 3 | 28 | 1956 | 35.400 | -101.300 | | 3.9 | 6F | PH Panhandle |
| **DPC** | **P** | **1925** | **7** | **30** | **1217** | **35.400** | **-101.300** | **0** | **5.4** | **6F** | **PH Panhandle** |
| *DPC* | *P* | *1925* | *7* | *31* | *1800* | *35.500* | *-101.100* | | *3.0* | *3F* | *PH White Deer* |

| *agency* | *cat* | *year* | *mo* | *da* | *time* | *lat* | *long* | *dep* | *magnitude* | *felt* | *geolocation & notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *DPC* | *P* | *1936* | *6* | *20* | | *35.700* | *-101.400* | | *3.9* | *4F* | *PH Borger (sequence)* |
| **DPC** | **P** | **1936** | **6** | **20** | **32412.0** | **35.700** | **-101.400** | **0** | **5.0** | **6F** | **PH Borger (sequence)** |
| DPC | P | 1966 | 7 | 20 | 9 459.5 | 35.700 | -101.200 | 33 | 4.1 | 5F | PH Borger |
| DPC | P | 1980 | 6 | 9 | 223710.1 | 35.500 | -101.050 | 5 | 4.3 | 5F | PH Pampa |
| PDE | I | 2006 | 02 | 18 | 54941.45 | 35.67 | -101.79 | 5 | 3.5 MLGS | .F | PH N Amarillo |
| **East-Central Panhandle** | | | | | | | | | | | |
| PDE | I | 2007 | 09 | 27 | 152102.06 | 35.47 | -100.11 | 5 | 3.0 LgGS | .. | PH E |
| **PDE** | **N** | **2007** | **10** | **07** | **135421.55** | **34.51** | **-100.15** | **5** | **3.1 LgGS** | **.** | **PH SE** |
| *PDE* | *I* | *2008* | *10* | *12* | *120815.77* | *35.62* | *-100.32* | *5* | *3.0 LgGS* | *.F* | *PH E* |
| **PDE** | **I** | **2008** | **10** | **14** | **030728.03** | **35.77** | **-100.71** | **5** | **3.7 MwRMT** | **4FM** | **PH E** |
| **Perryton** | | | | | | | | | | | |
| DPC | P | 1974 | 2 | 15 | 133349.9 | 36.380 | -100.520 | 24 | 4.5BUSGS | 5F | PH Perryton |
| **Silverton** | | | | | | | | | | | |
| DPC | S | 1925 | 7 | 29 | 1130 | 34.500 | -101.200 | | 3.3 | 4F | PH Silverton |

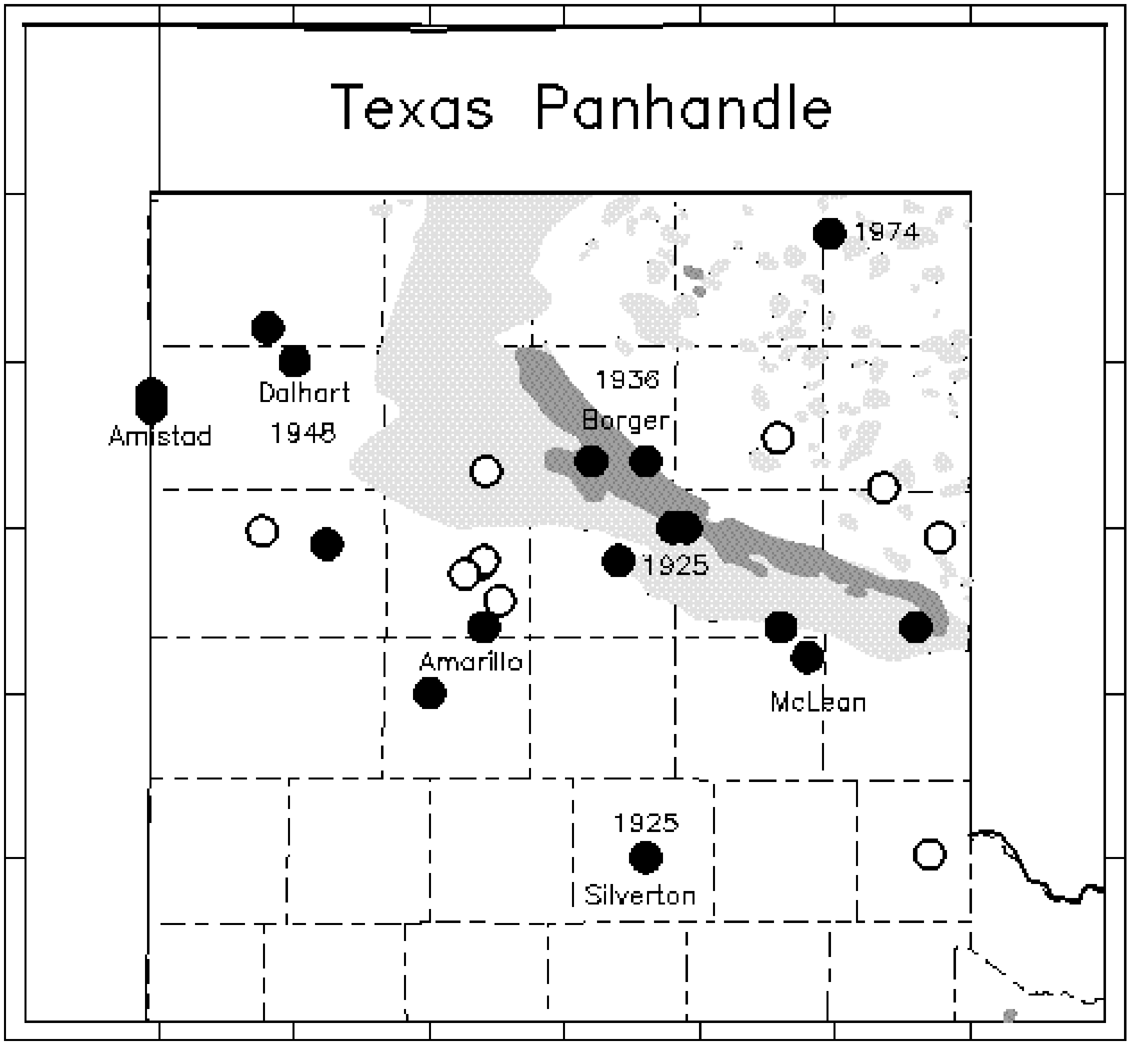


**Figure 7.** Earthquakes and oil and gas field in the Texas Panhandle. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC; dark shaded areas are oil fields from Galloway et al. (1983); light shaded areas are gas fields from Kosters et al. (1989).

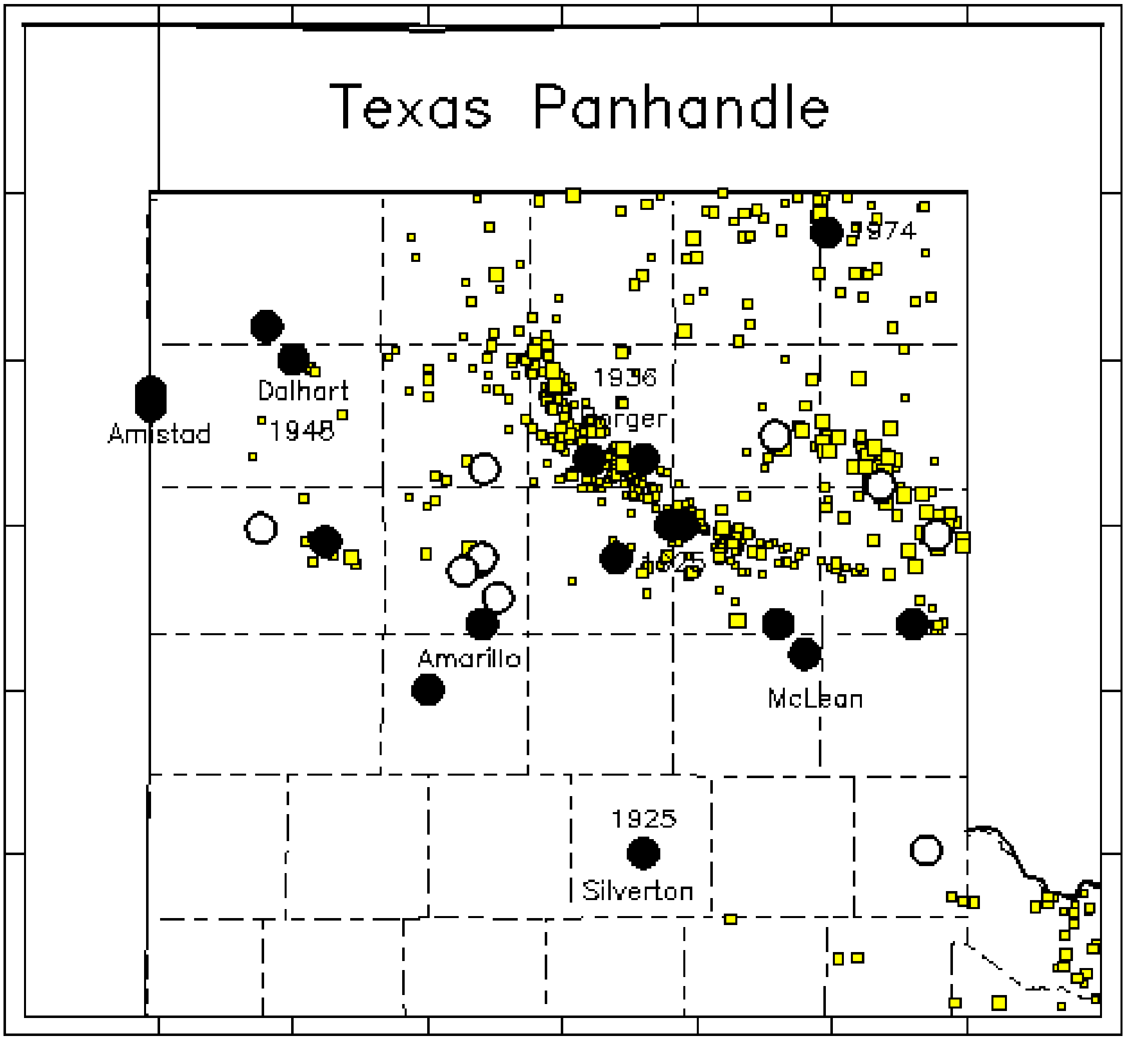


**Figure 8.** Earthquakes and class II injection wells in the Texas Panhandle. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC. Large, intermediate, and small symbols are wells with maximum monthly reported rates of > 100,000 BWPM (barrels of water per month), >10,000 BWPM, and >1000 BWPM.

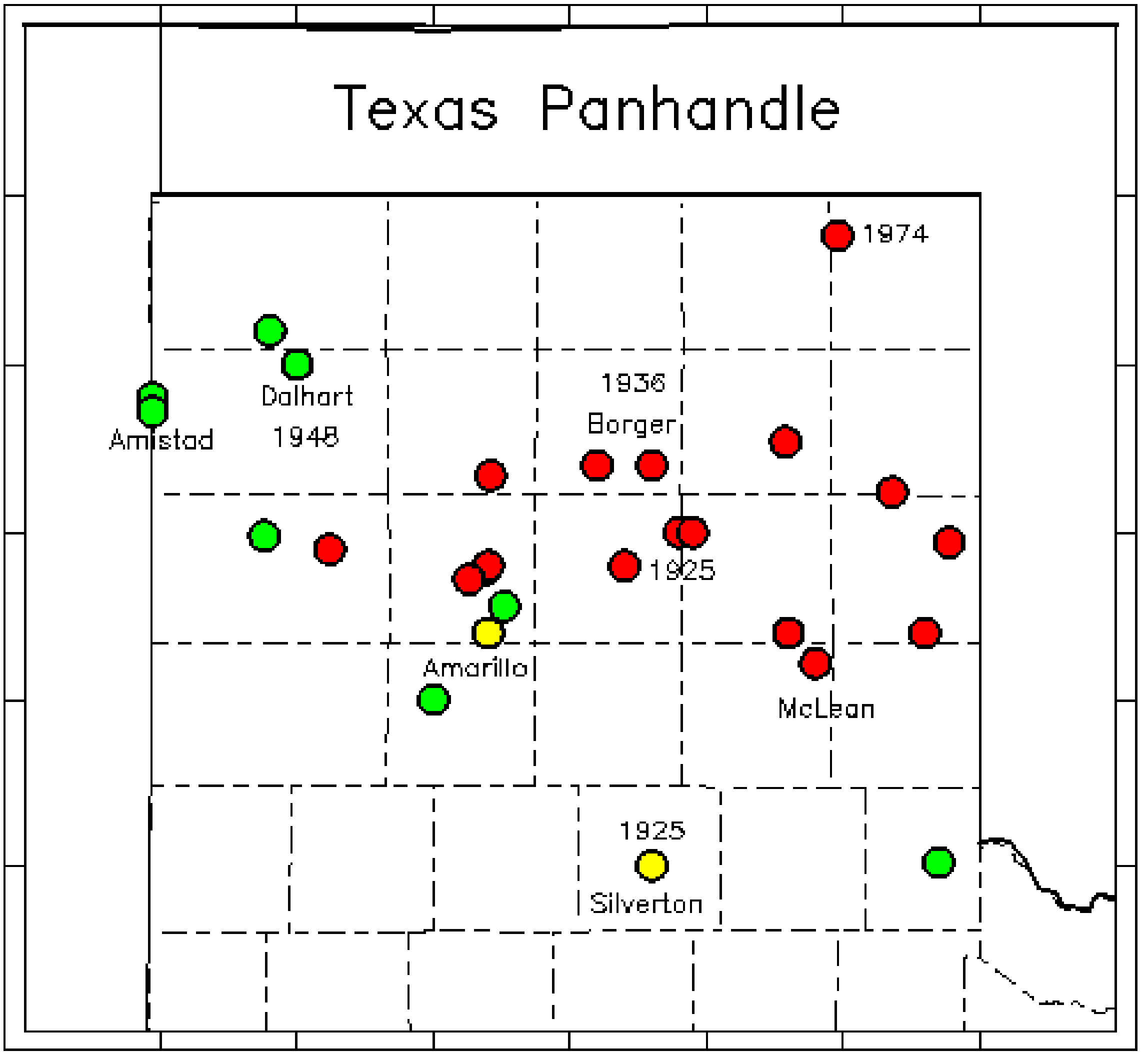


**Figure 9.** Categories assigned in this study to earthquakes (circles) in the Texas Panhandle. Symbol key: green – natural earthquakes; red – earthquakes occurring in close association to active oil fields, gas fields, or injection wells; yellow – possibly spurious events.

### 3.3 Texas Gulf Coast (GC)

In Texas, especially in the petroleum industry, the southeastern section of the state is usually simply called the Texas Gulf Coast region.

*Alice (near producing fields)* – Both the 1997 and 2010 earthquakes occurred within or on the boundary of the Stratten Field that had been producing oil and gas since 1938 (Bilich et al., 1998; Frohlich et al., 2012)

*Austin area (natural)* – There are no petroleum fields or injection wells in the Austin area, and this 1902 earthquake occurred well before there was any such development in Texas.

*Fashing, etc. (near or within producing fields)* – Earthquakes began being reported in this area south of San Antonio in the 1970's, long after it was populated and well after petroleum fields began being developed in the 1950's. All the well-located earthquakes in this area occur within or on the boundary of producing oil and gas fields; the most thorough investigations suggest the earthquakes are caused by extraction (Pennington et al., 1986; Davis et al., 1995).

*Hempstead, etc. (natural)* – When these earthquakes occurred (1887, 1910, 1914) there was no petroleum development in south or central Texas.

*Orange (natural or spurious)* – As discussed by Frohlich and Davis (2002), there is uncertainty about whether this event was an earthquake. However, at the time of its occurrence in 1952 there was no nearby petroleum development.

*Seguin (natural)* – This 1847 earthquake is known only from two contemporary reports. If it occurred it is of natural origin.

**Table 4.** Texas Gulf Coast (GC). 'Agency' is abbreviation of organization reporting this location (see Table 1); 'cat' is category assigned: N – natural, P – near producing oil or gas field; I – near active injection well; S – possibly spurious report; 'mo' is month of occurrence; 'da' is day of occurrence; 'lat' is reported latitude; 'long' is reported longitude; 'felt' indicates that NEIC reported felt information; 'geolocation' is Texas quadrant and nearby community name: WT – west Texas; PH – Panhandle; GC – Gulf Coast; NET – northeast Texas. Events in italics are aftershocks, defined as events in a sequence occurring within one month one another; main shock is in bold type.

| *agency* | *cat* | *year* | *mo* | *da* | *time* | *lat* | *long* | *dep* | *magnitude* | *felt* | *geolocation & notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alice** | | | | | | | | | | | |
| FD | P | 1997 | 3 | 24 | 223134.6 | 27.700 | -97.950 | 5 | 3.8 MnGS | 5F.. | GC Alice |
| PDE | P | 2010 | 4 | 25 | 021042.77 | 27.71 | -97.85 | 5 | 3.9 LgGS | 3F | GC Alice |
| **Austin area** | | | | | | | | | | | |
| DPC | N | 1873 | 5 | 01 | 0430 | 30.250 | -97.600 | | 3.1 | 4F | GC Manor |
| DPC | N | 1887 | 1 | 05 | 1757 | 30.150 | -97.060 | | 4.1 | 6F | GC Paige |
| DPC | N | 1902 | 10 | 09 | 1900 | 30.100 | -97.600 | | 3.9 | 5F | GC Creedmoor |
| **Fashing, etc.** | | | | | | | | | | | |
| DPC | P | 1973 | 12 | 25 | 246 | 28.820 | -98.200 | | 3.2 | 4F | GC Fashing |
| DPC | P | 1983 | 7 | 23 | 152435.4 | 28.820 | -98.180 | 5 | 3.4 | 5F | GC Fashing (previous activity) |
| DPC | P | 1984 | 3 | 3 | 1 330.0 | 28.870 | -98.500 | 5 | 3.9 | 5F | GC Pleasanton (several aftershocks |
| FD | P | 1991 | 7 | 20 | 233819.2 | 29.000 | -98.000 | 10 | 3.6 MnGS | 4F | GC Falls City |
| FD | P | 1993 | 4 | 09 | 122919.2 | 28.870 | -98.500 | 5 | 4.3 MnGS | 5D | GC Fashing |
| FD | P | 1993 | 5 | 1 | 153019.4 | 28.900 | -98.500 | 5 | 3.0 MnGS | 4F | GC Jourdanton |
| PDE | P | 2008 | 4 | 07 | 095112.98 | 28.92 | -98.04 | 5 | 3.9 MwSLM | 3FM | GC Fashing |
| PDE | P | 2010 | 3 | 08 | 234728.12 | 28.95 | -98.04 | 5 | 3.0 LgGS | 3F. | GC Fashing |
| PDE | P | 2010 | 12 | 21 | 135318.04 | 28.64 | -98.04 | 5 | 3.0 LgGS | ... | GC Fashing |
| **PDE** | **P** | **2011** | **10** | **20** | **122441.60** | **28.86** | **-98.08** | **5** | **4.8 MwRMT** | **5FM** | **GC Fashing** |
| *PDE* | *P* | *2011* | *11* | *12* | *103453.85* | *28.87* | *-98.21* | *5* | *3.5 LgGS* | *.F* | *GC Fashing* |
| PDE | P | 2012 | 2 | 04 | 124808.50 | 28.84 | -98.20 | 5 | 3.0 LgGS | .F | GC Fashing |
| PDE | P | 2012 | 6 | 24 | 085558.57 | 28.43 | -98.38 | 5 | 3.4 LgGS | .F. | GC Tilden |
| **Hempstead, etc.** | | | | | | | | | | | |
| DPC | N | 1887 | 1 | 31 | 2214 | 30.530 | -96.300 | | 3.3 | 4F | GC Wellborn |
| DPC | N | 1910 | 5 | 08 | 1730 | 30.100 | -96.000 | | 3.8 | 4F | GC Hempstead |
| DPC | N | 1914 | 12 | 30 | 0100 | 30.500 | -95.900 | | 3.3 | 4F | GC Anderson |
| **Orange** | | | | | | | | | | | |
| DPC | S | 1952 | 10 | 17 | 1548 | 30.100 | -93.800 | | 3.3 | 4F | GC Orange |
| **Seguin** | | | | | | | | | | | |
| DPC | N | 1847 | 2 | 14 | 0200 | 29.600 | -98.000 | | 3.6 | 5F | GC Seguin |

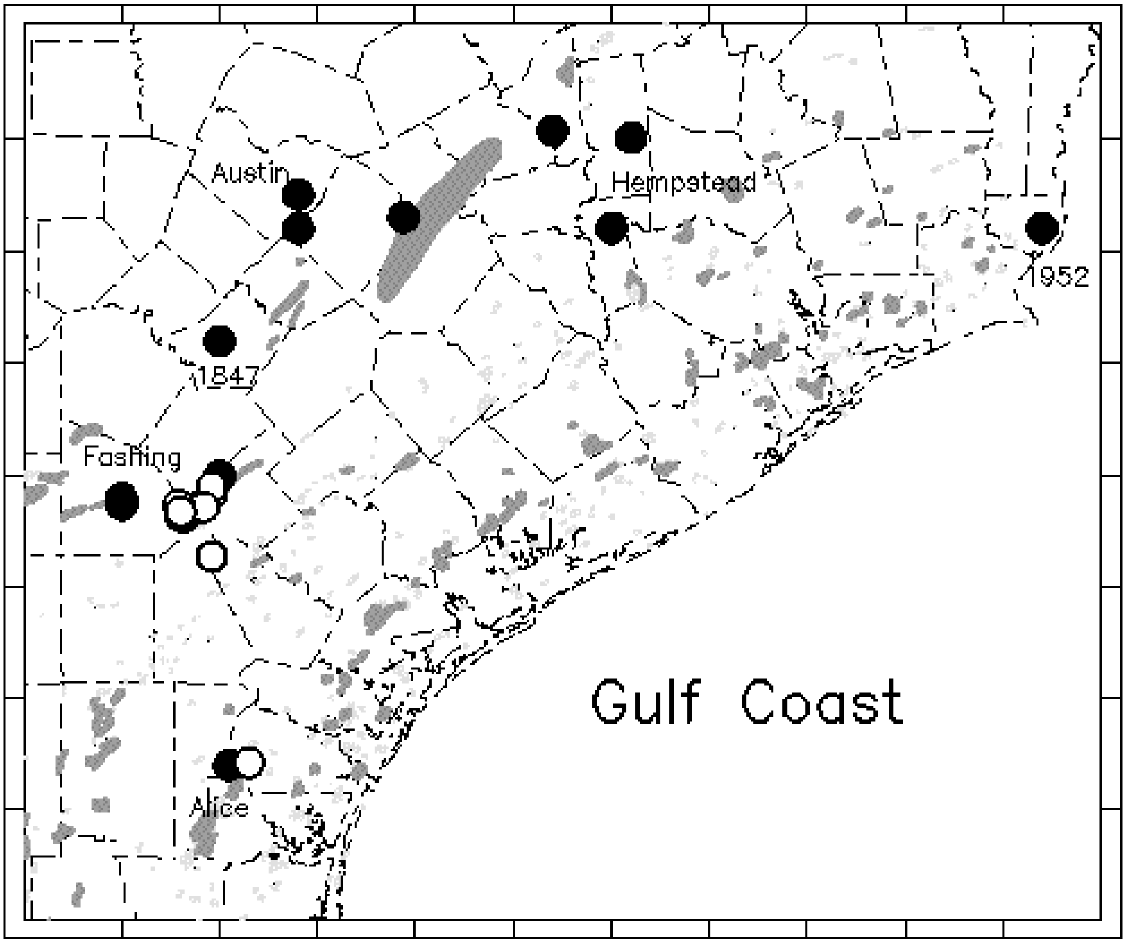


**Figure 10**. Earthquakes and oil and gas field along the Texas Gulf Coast. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC; dark shaded areas are oil fields from Galloway et al. (1983); light shaded areas are gas fields from Kosters et al. (1989).

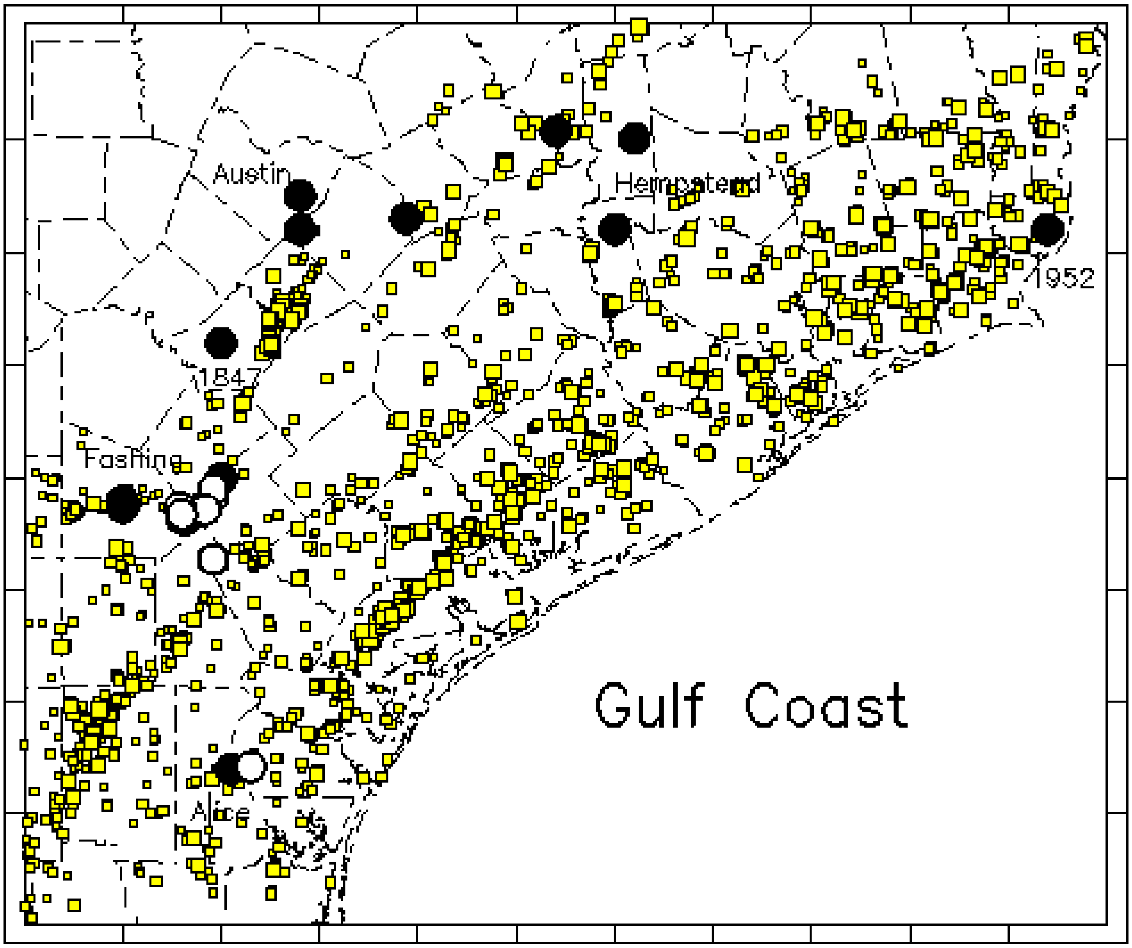


**Figure 11.** Earthquakes and class II injection wells along the Texas Gulf Coast. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC. Large, intermediate, and small symbols are wells with maximum monthly reported rates of > 100,000 BWPM (barrels of water per month), >10,000 BWPM, and >1000 BWPM.

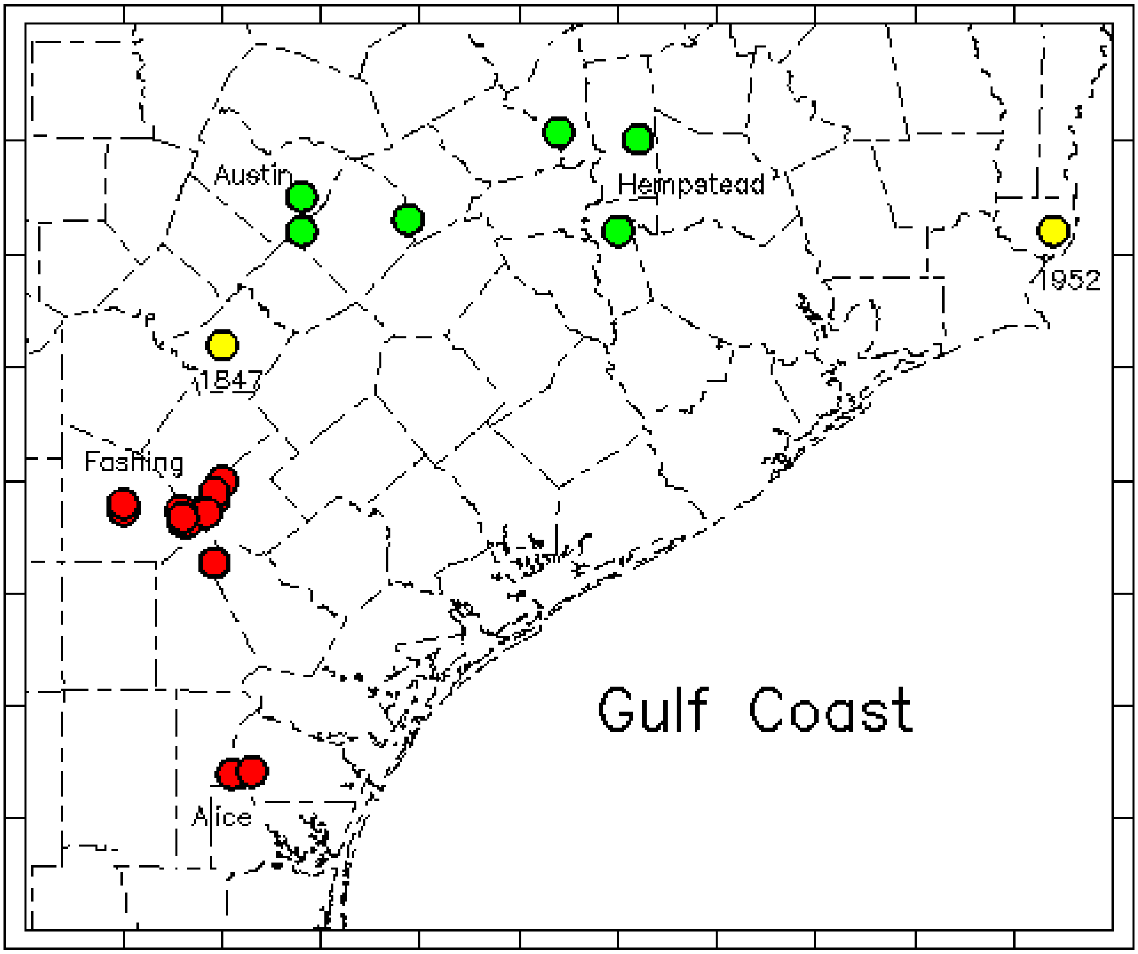


**Figure 12.** Categories assigned in this study to earthquakes (circles) along the Texas Gulf Coast. Symbol key: green – natural earthquakes; red – earthquakes occurring in close association to active oil fields, gas fields, or injection wells; yellow – possibly spurious events.

### 3.4 Northeast Texas (NET)

Although the northeastern section of the Texas is sometimes called East Texas, I will call it Northeast Texas to differentiate it from the southeastern part (the Gulf Coast), and the Panhandle, which is further north.

*Chico (natural or spurious)* – This earthquake is known only from a single report in the U.S.G.S. publication *U.S. Earthquakes 1950* (see Frohlich and Davis, 2002). At that time there was no nearby petroleum development.

*Cleburne and Johnson County (near injection wells)* – Earthquakes began being reported near Cleburne in Johnson County in 2009; none were larger than M3.0 before 2011. Analyses by Frohlich (2012), Howe (2012) and Howe-Justinic et al. (2012) suggest that all occurred near active injection wells.

*Dallas-Fort Worth (near injection wells)* - Earthquakes began being reported near the Dallas-Fort Worth airport in 2008. Analyses by Frohlich et al. (2010; 2011), Frohlich (2012), Reiter et al. (2012) suggest that these events may be associated with nearby injection wells. Janska and Eisner (2012) agree that the sequence occurred near wells but argue that it may be of natural origin.

*Gladewater (near producing field)* – This M4.7 1957 earthquake occurred within or near the largest producing oil field in the western hemisphere (see discussion in Frohlich and Davis, 2002)

*Hemphill (natural)* - When this 1964 earthquakes occurred I have found no nearby regional petroleum development. The felt area included the Sam Rayburn Reservoir and the Toledo Bend Reservoir; however, neither reservoir had been filled when the earthquake occurred, although the dam for the Sam Rayburn Reservoir was nearly finished (Frohlich and Davis, 2002).

*Jacksonville (natural)* – There are oil and gas fields in East Texas near where this 1981 earthquake occurred. However, a felt report study indicated the highest-intensity regions were well away from any fields (see Frohlich and Davis, 2002), and the event is probably natural.

*Mexia-Wortham (near producing fields)* – This highest-intensity region for this 1932 earthquake was centered on the Wortham oil field and the distribution of intensities indicated it had a very shallow focal depth. It was probably induced/triggered by extraction (Sellards, 1933; Frohlich and Davis, 2002).

*Mt. Enterprise Fault Zone (some natural and one near injection wells)* – The 1891 and 1981 East Texas earthquakes are natural, as one occurred before any petroleum development in Texas and the other occurred quite distant from any such development. However, the highest-intensity region for the 2012 M4.8 Timpson earthquake was situated near two high-volume injection disposal wells that had average injection rates averaging 100,000-200,000 BWPM (16,000-32,000 $m^3$/month) since 2006 (see Frohlich et al., 2013 - in preparation). The well API numbers are API# 4240133830000 and API# 42419312870000.

**Table 5.** Northeast Texas (NET). 'Agency' is abbreviation of organization reporting this location (see Table 1); 'cat' is category assigned: N – natural, P – near producing oil or gas field; I – near active injection well; S – possibly spurious report; 'mo' is month of occurrence; 'da' is day of occurrence; 'lat' is reported latitude; 'long' is reported longitude; 'felt' indicates that NEIC reported felt information; 'geolocation' is Texas quadrant and nearby community name: WT – west Texas; PH – Panhandle; GC – Gulf Coast; NET – northeast Texas. Events in italics are aftershocks, defined as events in a sequence occurring within one month one another; main shock is in bold type.

| *agency* | *cat* | *year* | *mo* | *da* | *time* | *lat* | *long* | *dep* | *magnitude* | *felt* | *geolocation & notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chico** | | | | | | | | | | | |
| DPC | S | 1950 | 3 | 20 | 1323 | 33.300 | -97.800 | | 3.3 | 4F | NET Chico |
| **Cleburne** | | | | | | | | | | | |
| PDE | I | 2011 | 7 | 17 | 65800.04 | 32.42 | -97.08 | 5 | 3.0 LgGS | 4F. | NET Cleburne |
| PDE | I | 2012 | 1 | 18 | 223054.96 | 32.37 | -97.49 | 5 | 3.3 LgGS | 4F. | NET Cleburne |
| *PDE* | *I* | *2012* | *6* | *15* | *070233.17* | *32.46* | *-97.27* | *5* | *3.3 LgGS* | *4F.* | *NET NW of Cleburne* |
| **PDE** | **I** | **2012** | **6** | **24** | **174644.45** | **32.47** | **-97.29** | **5** | **3.5 LgGS** | **4F.** | **NET NW of Cleburne** |
| **Dallas-Fort Worth** | | | | | | | | | | | |
| PDE | I | 2008 | 10 | 31 | 50154.91 | 32.84 | -97.03 | 5 | 3.0 LgGS | 4F | NET DFW |
| **PDE** | **I** | **2009** | **5** | **16** | **162406.57** | **32.79** | **-97.02** | **8** | **3.3 LgGS** | **4F** | **NET DFW** |
| *PDE* | *I* | *2009* | *5* | *16* | *165837.69* | *32.85* | *-97.10* | *5* | *3.0 LgGS* | .. | *NET DFW* |
| **PDE** | **I** | **2012** | **9** | **30** | **040500.93** | **32.84** | **-96.98** | **5** | **3.4 LgGS** | **4F** | **NET DFW** |
| *PDE* | *I* | *2012* | *9* | *30* | *040902.72* | *32.81* | *-96.96* | *5* | *3.1 LgGS* | *.F* | *NET DFW* |
| **Gladewater, Hemphill** | | | | | | | | | | | |
| DPC | P | 1957 | 3 | 19 | 1637 | 32.600 | -94.700 | | 4.7 | 5F | NET Gladewater (sequence) |
| DPC | N | 1964 | 4 | 24 | | 31.300 | -93.800 | | 4.4 | 6F | NET Hemphill (sequence) |
| **Mexia Wortham, Jacksonville** | | | | | | | | | | | |
| DPC | I | 1932 | 4 | 9 | 1017 | 31.700 | -96.400 | | 4.0 | 6F | NET Mexia-Wortham |
| DPC | N | 1981 | 11 | 6 | 123640.3 | 31.950 | -95.920 | 5 | 3.3 | 5F | NET Jacksonville |
| **Mt. Enterprise fault zone** | | | | | | | | | | | |
| DPC | N | 1891 | 1 | 8 | 0600 | 31.700 | -95.200 | | 4.0 | 6F | NET Rusk |
| DPC | N | 1981 | 6 | 9 | 14631.0 | 31.760 | -94.280 | 5 | 3.2 | 3F | NET Center |
| *PDE* | *I* | *2012* | *5* | *10* | *151538.84* | *31.96* | *-94.46* | *5* | *3.9 MwRMT* | *5FM* | *NET Timpson* |
| **PDE** | **I** | **2012** | **5** | **17** | **81200.99** | **31.93** | **-94.37** | **5** | **4.8 MwRMT** | **5FM** | **NET Timpson** |
| **Texas-Oklahoma border** | | | | | | | | | | | |
| DPC | N | 1934 | 4 | 12 | 140 | 33.900 | -95.500 | | 4.2 | 5F | NET Trout Switch |
| FD | N | 1997 | 5 | 31 | 32641.3 | 33.180 | -95.970 | 5 | 3.4 MnGS | 4F | NET Commerce |

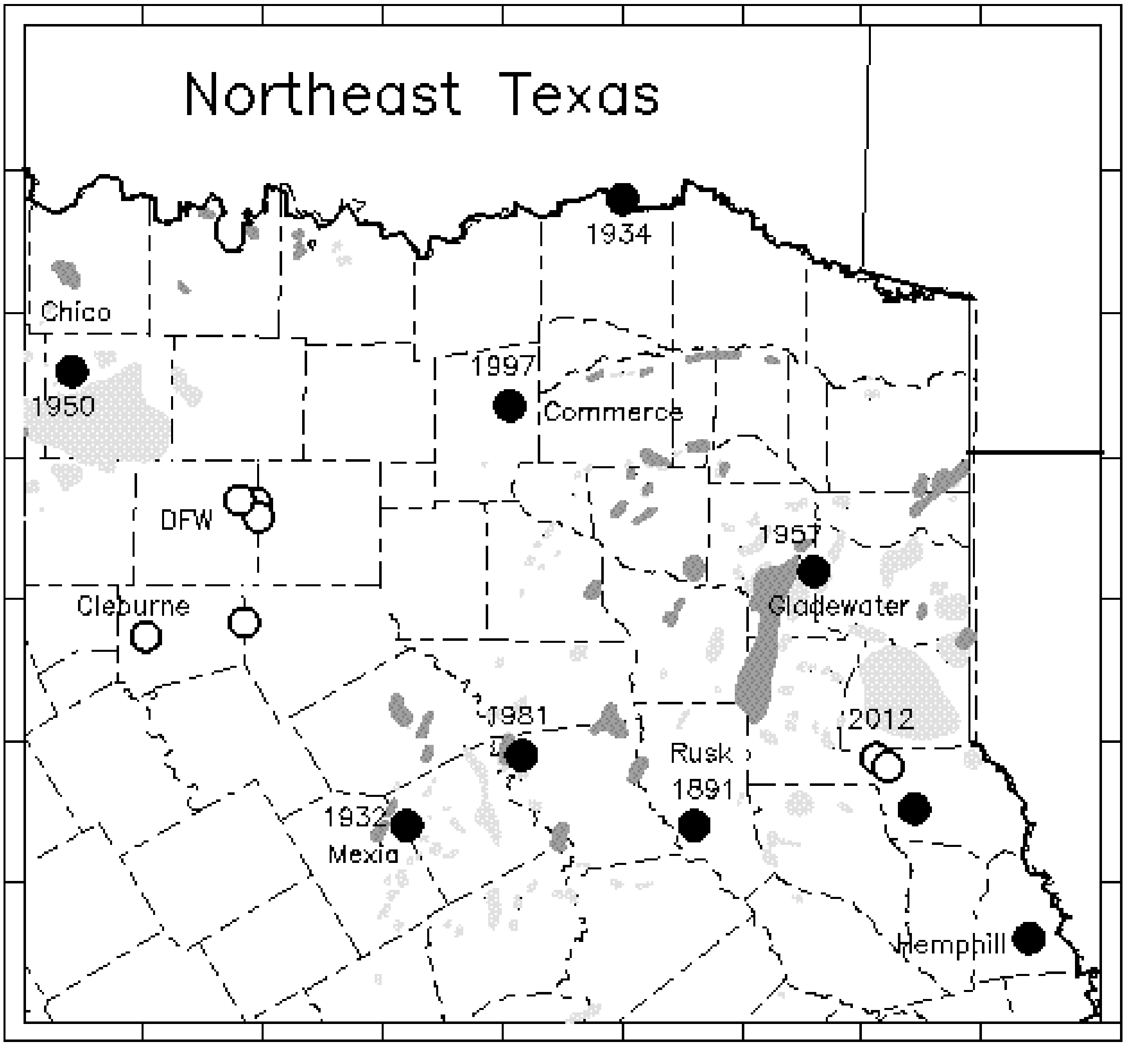


**Figure 13.** Earthquakes and oil and gas field in northeast Texas. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC; dark shaded areas are oil fields from Galloway et al. (1983); light shaded areas are gas fields from Kosters et al. (1989).

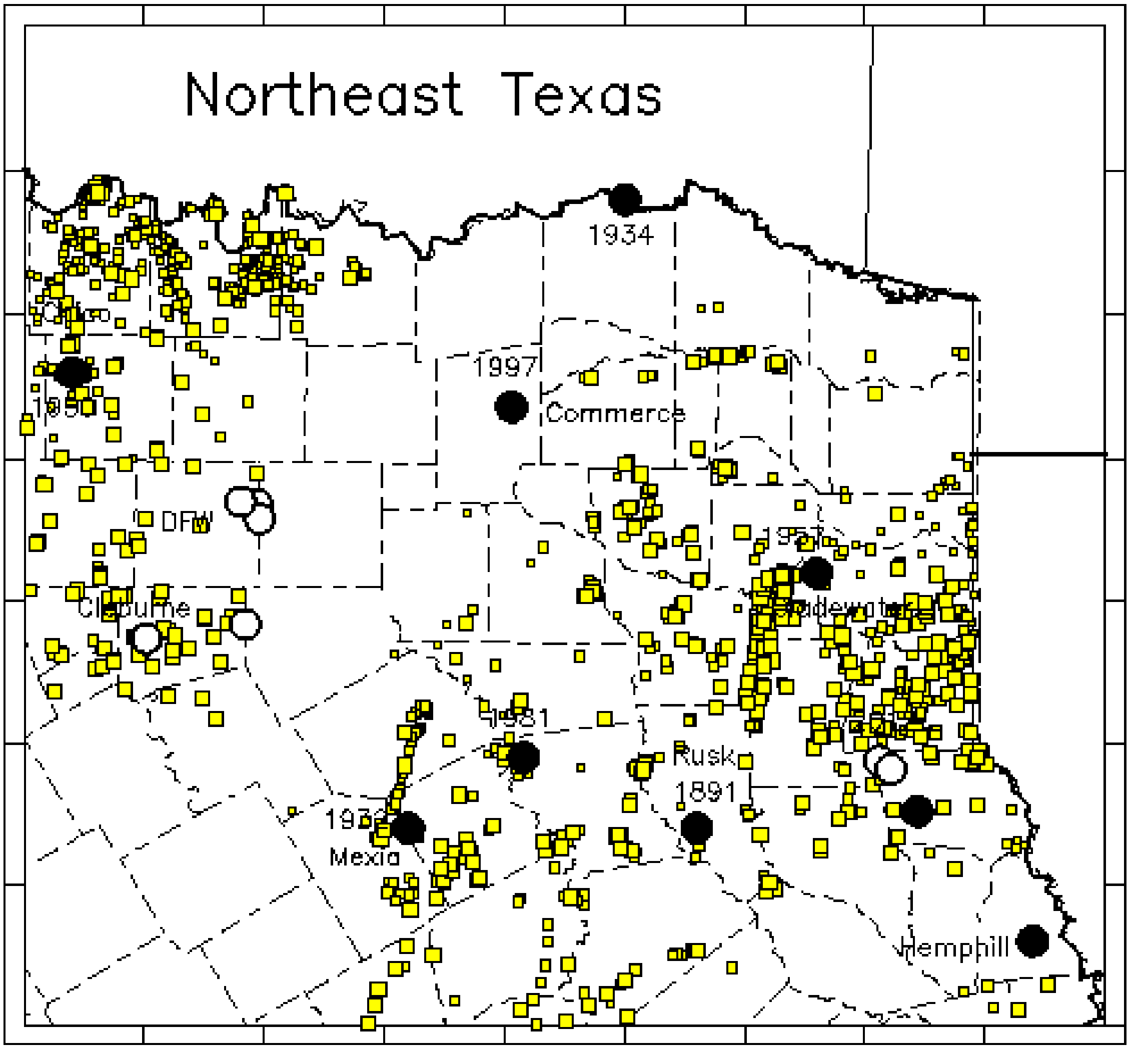


**Figure 14.** Earthquakes and class II injection wells in northeast Texas. Filled circles are events with magnitudes of 3 or greater occurring 2000 and earlier from compilation of Frohlich and Davis (2002); open circles are events 2001 and later reported by the NEIC. Large, intermediate, and small symbols are wells with maximum monthly reported rates of > 100,000 BWPM (barrels of water per month), >10,000 BWPM, and >1000 BWPM.

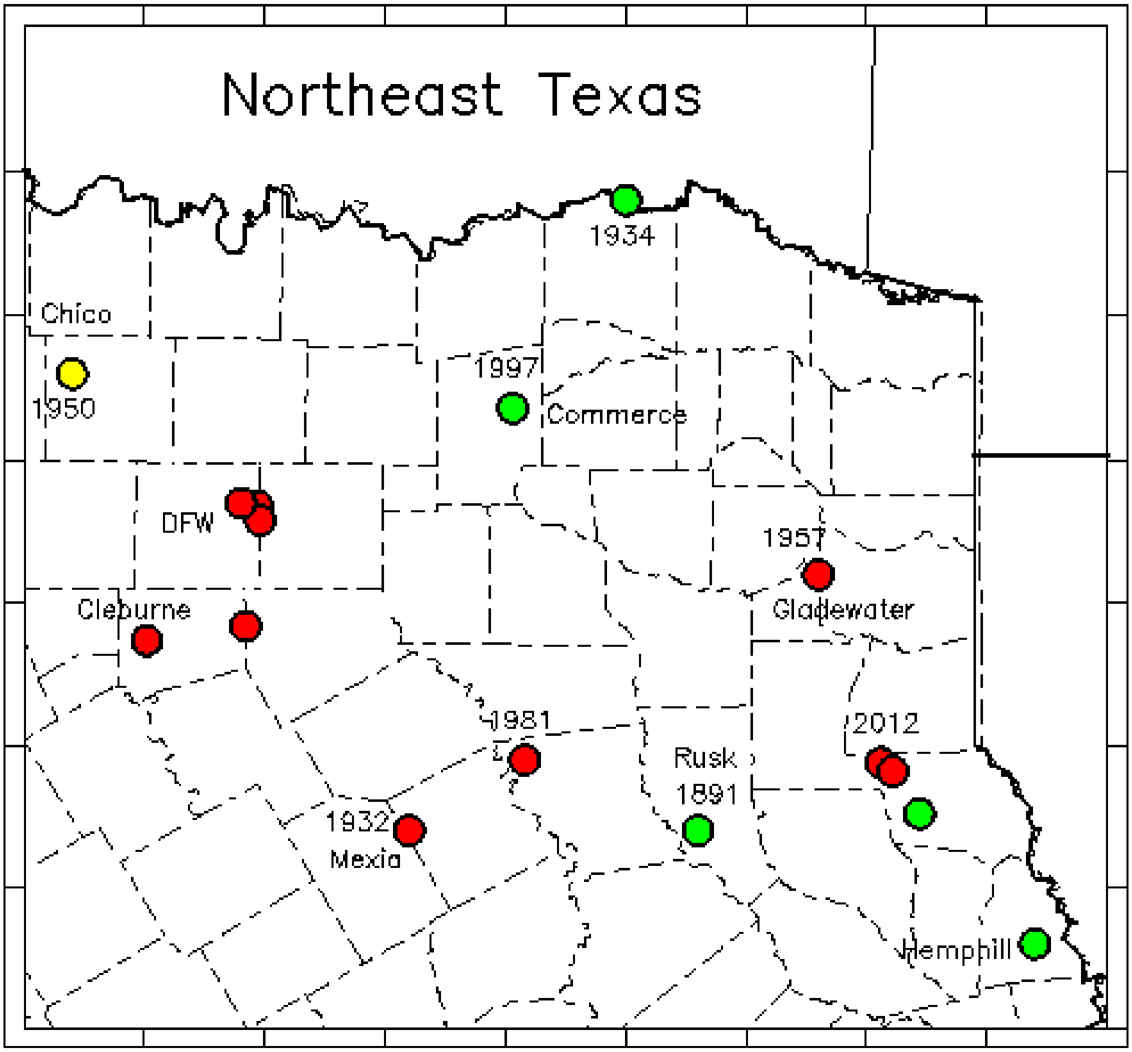


**Figure 15.** Categories assigned in this study to earthquakes (circles) in northeast Texas. Symbol key: green – natural earthquakes; red – earthquakes occurring in close association to active oil fields, gas fields, or injection wells; yellow – possibly spurious events.

**4. DISCUSSION**

As noted in Section 1.4, it is far easier to identify earthquakes that are in close contact with human enterprise (QUICHE) than it is to agree whether particular events are induced or triggered by humans. After removing aftershocks and possibly spurious events from Tables 2-5, the overall proportion of QUICHE earthquakes in Texas is ~65 per cent (Table 6). The proportions of QUICHE earthquakes are similar in each of the four geographic; the smallest fraction was 60 percent in west Texas; the largest fraction was 71 per cent in the Panhandle.

The raw data in Table 6 also indicate that proportions of QUICHE earthquakes have increased over time; there are 20 percent of QUICHE earthquakes prior to 1950; 68 per cent between 1950 and 1999; and 86 per cent since. However, the time-dependence in these figures may be midleading; over the past century there have been vast changes in Texas' population density in regional seismograph station coverage for Texas. A century ago there were no oil fields, gas fields, or injection wells in Texas. All these factors affect the identification and location of small-magnitude earthquakes and over time make it more likely that an earthquake will be near a producing field or injection well. Also, the QUICHE-event totals are dominated by events in a few areas; e.g., 12 are from the region southeast of San Antonio that includes Fashing; 7 are near Dallas-Fort Worth and Cleburne in northeast Texas; together these two categories make up almost a third of the total.

Nevertheless, the data in Table 6 show unequivocally that a significant proportion of Texas earthquakes occur in close association with human activity. These QUICHE events occur in numerous different locations in all four parts of Texas; they include earthquakes occurring within and near producing oil and gas fields—events associated with extraction—as well as earthquakes associated with injection for both waterflooding and waste disposal.

But, how strong is the evidence that the QUICHE-identified earthquakes really are induced or triggered by humans? Which earthquakes are probably caused or triggered by humans, and which are not? The answers to these questions are different for the seismicity in different regions:

• In northeast Texas, in spite of the counter-arguments of Janska and Eisner (2012), the evidence that injection caused earthquakes near Dallas-Fort Worth and in Johnson County (including Cleburne) is quite strong (see Frohlich et al., 2011; Frohlich, 2012). It is also plausible that the Mexia-Wortham 1932 earthquake and the 1957 Gladewater earthquake were triggered by the huge volumes of petroleum extracted from nearby fields.

• Along the Gulf Coast, it is plausible that the earthquakes near Fashing and neighboring regions are triggered by production in various fields. These fields were developed in the 1950's and there are no reports of earthquakes occurring prior to the 1970's; earthquakes have been numerous since, and all occur within or at the boundary of active fields.

• In west Texas, the situation is similar for the Snyder earthquakes in the Cogdell field, where earthquakes began only after the field was developed and after the field underwent massive waterflooding operations. For earthquakes in the Permian basin the situation is less clear; although earthquakes do seem to occur in and near petroleum fields, over much of the region the geographic extent of such fields is nearly ubiquitous. Although few or no earthquakes were reported prior to the development of the fields, the population prior to development was so low it is unclear that small earthquakes would be noticed.

• In the Panhandle, the situation is similar to that in the Permian Basin. Although earthquakes have only been confirmed following the development of petroleum fields beginning in the 1910's, before that time the population density was very low. The development of petroleum fields quickly covered large geographic areas; and, some Panhandle earthquakes are clearly of natural origin, occurring in regions where there are no petroleum fields or injection wells. Although there are numerous QUICHE-identified earthquakes in the Panhandle, at present it is unclear whether or not these are caused by human activity.

**Table 6:** Fractions of QUICHE earthquakes in each geographic region of Texas; quakes that that occurred in/near active petroleum fields or injection disposal wells. Data are earthquakes with M3.0 and larger as listed in Tables 2-5. Fractions in table do not count aftershocks (in italics in tables) or possibly spurious events (labeled 'S' in category column

| *Region* | *before 1950* | *1950-2000* | *2000-2013* | *All* | *All %* |
|---|---|---|---|---|---|
| West Texas | 0/7 | 12/16 | 9/12 | 21/35 | 60 |
| Panhandle | 3/4 | 6/10 | 8/10 | 17/24 | 71 |
| Gulf Coast | 0/6 | 7/7 | 7/7 | 14/20 | 70 |
| Northeast Texas | 1/3 | 1/5 | 7/7 | 9/15 | 60 |
| All of Texas | 4/20 | 26/38 | 31/36 | 61/94 | 65 |
| All % | 20 | 68 | 86 | 65 | |

## 5. SUGGESTIONS FOR FUTURE RESEARCH

### 5.1 Additional Regional Analyses of USArray Data

The passage of the USArray Transportable Array provides an opportunity to identify and accurately locate small earthquakes in parts of the U.S where, as in Texas, there are few continuously operating seismic stations. In much of Texas earthquakes with magnitudes smaller than M3.5-3.0 go unreported, unlocated, and/or unrecorded

Frohlich's (2012) two-year survey of seismicity within the Barnet Shale demonstrates what analysis of USArray data can teach us, and raises questions that might be resolved by additional survey:

- The Barnett survey found numerous earthquakes occurring near injection wells. Would surveys in other geographic regions find a similar result?
- The Barnett survey found that well-located earthquakes only occurred near wells where maximum injection volumes exceeded a critical rate, 150,000 BWPM. Would surveys in other regions also identify a critical rate, presumably different than observed in the Barnett? If so, can we understand how this rate depends on properties of the subsurface, such as permeability, regional stress etc.?
- In the Barnett survey most of the wells associated with seismicity had been injecting for a year or more before the identified earthquakes occurred[3]. Would this also be true

[3] Of course, shale gas development in the Barnett intensified only after about 2004 and injection at many disposal wells initiated only after 2007, while the Barnett survey identified small earthquakes occurring

in other geographic areas?

• In the Barnett Shale the great majority of injection wells aren't associated with any seismicity; most of the earthquakes identified occurred in Johnson County, while other counties with apparently similar injection wells experienced no seismicity. Would other geographic regions exhibit the same tendency for injection-associated earthquakes to be confined to particular subregions?

Some of these questions might be resolved by surveys of other geographic regions including the Eagle Ford in Texas, the Bakken Shale in North Dakota, the Haynesville Shale in eastern Texas and Louisian, the Marcellus Shale in Pennsylvania and surrounding states, and the Permian Basin of west Texas. Most previous investigations of induced/triggered seismicity are initiated only after earthquakes disturb citizens. Surveys such as Frohlich's (2012) Barnett Shale survey—surveys that aren't initiated by media reports of earthquakes—have the potential to provide better statistical information about the incidence of triggered seismicity, and a profile of the geologic properties and injection histories of wells that appear to be responsible.

In Texas, I am about to undertake projects surveying USArray data and injection wells in the Cogdell Field near Snyder, in the Haynesville Shale of Texas-Louisiana, and in the Eagle Ford of Texas. An M4.8 earthquake occurred in the Eagle Ford on 20 October 2011; Brunt et al. (2012) have reported our preliminary analysis of this earthquake. Undoubtedly other scientists may also investigate seismicity in these geographic areas.

### 5.2 Focal Depths for Panhandle Earthquakes

Outside of west Texas where the ~M6 earthquakes of 1931 (Valentine) and 1995 (Alpine) occurred, the largest earthquakes in Texas are in the Panhandle. As noted in Section 4.2, no Panhandle earthquakes are known prior to about 1920 when oil fields began to be developed; subsequently a significant fraction of Panhandle earthquakes occur in or near oil and gas fields. Nevertheless, most previous investigators haven't concluded these earthquakes are triggered or induced although they obviously fall into the category of earthquakes "associated with oil and gas field".

An important unresolved question concerns the focal depth of Panhandle earthquakes. If they are shallow (depth < ~5 km) it is plausible they are triggered or induced; if they are deeper they are probably of natural origin. A possible strategy for resolving this would be to compare recorded seismograms for Panhandle earthquakes to synthetics.

• Several small Panhandle earthquakes occurred in 2008-2010 while USArray stations operated in this region. If appropriate information about crustal structure can be found synthetics could be constructed using reflectivity or other methods appropriate at event-station distances of 200 km and less.

• The earthquakes of 30 July 1925 and 20 June 1936 had magnitudes of 5.4 and 5.0, respectively. According to Heck (1927), in 1925 The nearest operating seismograph stations were in Tucson, Arizona; Denver, Colorado; St. Louis, Missouri; and New

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between November 2009 and September 2011. Thus it is possible that small, undetected earthquakes occurred earlier than November 2009.

Orleans, Louisiana. If records for these earthquakes can be found, it is possible that synthetic modeling would provide constraints on focal depth.

### 5.3 Subsurface Faulting

The Ewing (1990) *Tectonic Map of Texas* is the best publicly available compilation of subsurface faulting in the state. However, this compilation is more than 20 years old and if an updated map/database of faulting were to be compiled, it would provide a useful starting place for assessing possible relationships between induced/triggered seismicity and faulting. Some of this information has been compiled by, and is available for purchase, from GeoMap Company. However, their maps are proprietary and it would require permissions from this company to publish the updated information.

Typically private companies have collected considerable amounts of proprietary information about subsurface structure in regions within Texas where petroleum fields and injection disposal wells are situated. Obviously this information would be immensely valuable for assessing the relationship between seismic activity and both petroleum production and wastewater injection. If possible, it would be desirable to develop an industry/university or industry/government collaborative program to share this information. Up to the present the efforts of myself and my colleagues at the University of Texas to do this have been unsuccessful; that is, we have been unable to reach agreements with individual companies about sharing proprietary information; nor were we successful in a 2010 attempt to form a consortium of companies to address these issues.

### 5.4 Updated Compilation of Oil and Gas Fields for Texas

The Galloway et al. (1983) and Kosters et al. (1989) atlases of oil and gas fields in Texas provide a valuable historical summary of the locations and statistical properties of the state's petroleum fields; the databases for summaries were updated and published in digital form by the University of Texas Bureau of Economic in the 1990's. It would be useful if this information was updated yet again.

Data concerning the locations and characteristics of wells is collected routinely by the Texas Railroad Commission, and this information is publicly available on their website. The website is not user-friendly, and several companies, including IHS, Inc., and GeoMap Company routinely compile this information and make it available to subscribers in various forms. One possible strategy for updating field information would be to develop an agreement or contract with these commercial companies to provide and make publicly available some elements of this information.

### 5.5 Digitizing Railroad Commission Information Prior to 1990

Nowadays the Texas Railroad Commission information is compiled in a relational database; however, information for wells prior to about 1990 was collected on paper forms and stored on microfilm. This information is stored in file cabinets and is available to the public. Obviously, pre-1990 information would be useful for assessing relationships between injection/production history and regional seismicity. Collecting this information would be labor-intensive but may be worthwhile for selected fields.

### 5.6 Operating Additional Seismograph Stations in Texas

Between 1980 and 2000 about four continuously operating three-component seismograph stations in Texas provided data available for routinely locating regional seismic events [Hockley (HKT) near Houston; Junction (JCT) in central Texas; Lahitas (LTX) in West Texas; Lubbock (LBTX) in the Panhandle]. During this period it is likely that catalogs of earthquake activity are complete down only to about M3.5.

Today, following the passage of the EarthScope USArray Transportable Array, there are about five additional permanent stations [Abilene (ABTX) in central Texas; Kingsville (KVTX) in south Texas; Nacogdoches (NATX) in east Texas; Jarrell (adopted TA station 435B); Artesia Wells (adopted TA station 833A) in south Texas. This isn't adequate for identifying or locating small earthquakes, considering that Texas has dimensions of 1265 km X 1055 km and a surface area of 690,000 $km^2$.

However, if we hope to routinely identify regional earthquakes with magnitudes between M2.5 and M3.5 and locate them with enough accuracy to associate them with individual injection wells, operating additional seismograph stations in Texas is desirable.

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