

PROJECT REPORT

For

DETERMINISTIC EVALUATION OF
INDUCED SEISMIC HAZARD FOR
CPNPP

Independent Review Required

YES

☒ NO

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PROJECT REPORT
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NO. TXUT-001-PR-018

REV. 1

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Attachment A

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Attachment B

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1.0 Introduction and Overview

Data Report, TXUT-1908-01 was developed to address human-made hazards as prescribed in NUREG 0800, Standard Review Plan, Section 2.5.1. This study concluded that there were no immediate safety issues for the CPNPP. However, the study provided four recommendations:

1. Develop a local seismic monitoring program that can detect small earthquakes ($m_b = 1$ to 3). Monitor the location and size of each earthquake, and periodically (i.e. every six months) investigate whether the rate of seismicity is changing. Because fluid injection slowly builds pressure in a reservoir, it is likely that seismicity, if conditions were favorable for it to occur, would build in intensity with time, allowing remedial action before an event of damaging magnitude would occur.
2. A moratorium on injection within a certain distance of the site might be considered to reduce potential future risk of induced earthquakes. Such a restriction should have little economic effect on the region (this is not limiting economic development of a resource), so it seems a reasonable measure considering the uncertainty in assessing the true risk.
3. The production of gas development should be allowed to proceed naturally to avoid the project site being a place of pore pressure gradient which could potentially increase the risk of seismicity.
4. Further study may be warranted to more comprehensively model the potential risk of seismicity along the lines of the methods of Segall and Fitzgerald (1998) and Davis and Pennington (1989). A problem with the modeling approach is the inability to eliminate uncertainty in the input data (in situ stress magnitudes, permeability distributions, locations and condition of pre-existing faults, etc.), so local monitoring of $m_b < 3$ earthquakes is probably a preferable initial route.

On May 4, 2011 during a conference call, it was agreed that recommendations 2 and 3 were not within Luminant's control. However, recognizing that the increased micro-seismicity in the Dallas-Fort Worth airport area is likely due to injection operations related to gas extraction of the Barnett Shale since TXUT-1908-01, Rev. 0 was completed in 2007, Luminant commissioned a study to specifically address recommendations 1 and 4 above.

The study involved the following components:

- Obtain and analyze 18 months of broadband, digital seismic data collected at four seismograph stations surrounding the CPNPP to search for small, regional earthquakes.
- Collect and summarize injection well locations, depths, periods of injection and quantities.
- Review recent literature concerning earthquakes induced by fluid injection, focusing particularly on recent activity and on implications for potential hazard at the CPNPP.
- Develop a hypothetical earthquake source model for performing a deterministic, parametric analysis to estimate the ground motion at the CPNPP location.

During the 18-month study period (see Attachment A), only a single earthquake was identified within 35 km of CPNPP; a very well-recorded M2.3 earthquake that occurred about 10 km WNW of the CPNPP. For this earthquake, the preferred epicenter at 32.334°N, 97.895°W was situated

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within 5 km of several injection wells. The closest well, at a distance of 1 km from the epicenter, injects at a depth of 1.6 km into the Barnett Shale Formation; with injection rates ~100,000 barrels/month between 2007 and 2010. The highest rates were from a well 4 km from the epicenter that injects at a depth of 2.9 km into the Ellenburger Limestone Formation. The rates were variable but about 150,000 barrels/month between 2007 and 2010, and for one month in 2009 as high as 550,000 barrels. An analysis of earthquakes in the Fort Worth Basin that were probably induced by the disposal of frack fluids finds that their magnitudes are small (M3.3 or less) and, where depth information is available, their focal depths appear to be at or slightly below the depths of injection. Thus, future induced earthquakes near CPNPP are likely to have magnitudes of 3.5 or smaller, and focal depths of 1.5-5 km.

An analysis of a compilation of well-documented injection-induced earthquakes (see Attachment B) found that with two exceptions, events with magnitudes exceeding M4.0 all occur in environments where natural earthquakes with larger magnitudes occur within 100 km of the well. The only exceptions (Snyder, TX; M4.6 in 1978 and M4.4 in 2011) were in a field undergoing decades-long waterflooding at more than 100 wells spaced on a ½-km grid. However, with magnitudes of M4.6 and M4.4 and a distance of 290 km from the CPNPP site, the Snyder earthquakes pose no physical threat to the facility.

The compilation found no examples where induced earthquakes having magnitudes exceeding M3.5 occurred near injection wells used for waste disposal in environments where the largest nearby natural earthquakes had magnitudes of 3.5 or less. Although 10-15 injection wells occur within 15 km of CPNPP, this analysis suggests that if these were to induce earthquakes, their magnitudes would be smaller than M3.5 (Attachment B).

2.0 Calculation of Ground Motions and Site Response

Results from the studies completed in Attachments A and B were used to develop a hypothetical human-induced earthquake to deterministically estimate the resulting ground motion at the CPNPP. This required the estimation of the magnitude, distance from the site and focal depth of the event.

One of the conclusions in Attachment A is that from the monitoring data and injection rates, induced earthquakes in the vicinity of the CPNPP are likely to have magnitudes of 3.5 or less and will occur at depths of 2-5km. Further, the single recorded event noted in Attachment A occurred about 10km from the CPNPP and about 5km from the nearest injection wells. The closest noted injection wells to the CPNPP are about 5km, thus constraining distances selected were 0 and 5km.

Calculations for ground motion and site response were performed for the following four earthquake magnitude-distance-depth combinations.

Description	Magnitude (m_{blg})	Distance	Depth
RealisticCase	3.5	0 and 5km	3 km
WorstCase	4.5	0 and 5km	2 km

The model for ground motion on rock, the model for aleatory uncertainty on rock, and the site-specific model for site response were the same used in Section 2.5.2 of the COLA to develop

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the GMRS. The ground-motion model for rock is given by EPRI (2004), the model for aleatory uncertainty in rock ground motion is given by EPRI (2006), and the data and methodology for site-response calculations are given in Section 2.5.2.5 of the COLA.

The rock ground motions were computed 1-sigma (or 84th -percentile) response spectra, where the standard deviation includes both the aleatory uncertainty given by EPRI (2006) and the epistemic uncertainty given by the 9 alternative equations in EPRI (2004) and by the m_{bLg} to moment-magnitude conversion.

In addition to the rock response spectra, the site-response calculations require specification of the strong-motion duration associated with each rock spectrum. The duration is calculated in the table below, using as inputs the magnitude, distance, and depth, and employing standard seismological relations between magnitude, seismic moment, corner frequency, and duration (see, for example, Rathje and Ozbey, 2006) and using stress-drop and crustal Vs values typical of the central and eastern United States.

Lg Magnitude m_{bLg}	Moment Magnitude M	Distance R (km)	Depth h (km)	Seismic Moment Mo (dyn-cm)	Corner Frequency fc (Hz)	Duration T (sec)
3.5	3.41	0	3	1.46E+21	7.45	0.28
4.5	4.16	0	2	1.95E+22	3.14	0.42
3.5	3.41	5	3	1.46E+21	7.45	0.43
4.5	4.16	5	2	1.95E+22	3.14	0.59

The resulting spectra are shown in Figure 1, where they are compared to the DCD spectrum (which is anchored at 0.3g) and to the site-specific spectrum (which is equal to the DCD spectrum anchored at 0.1g).

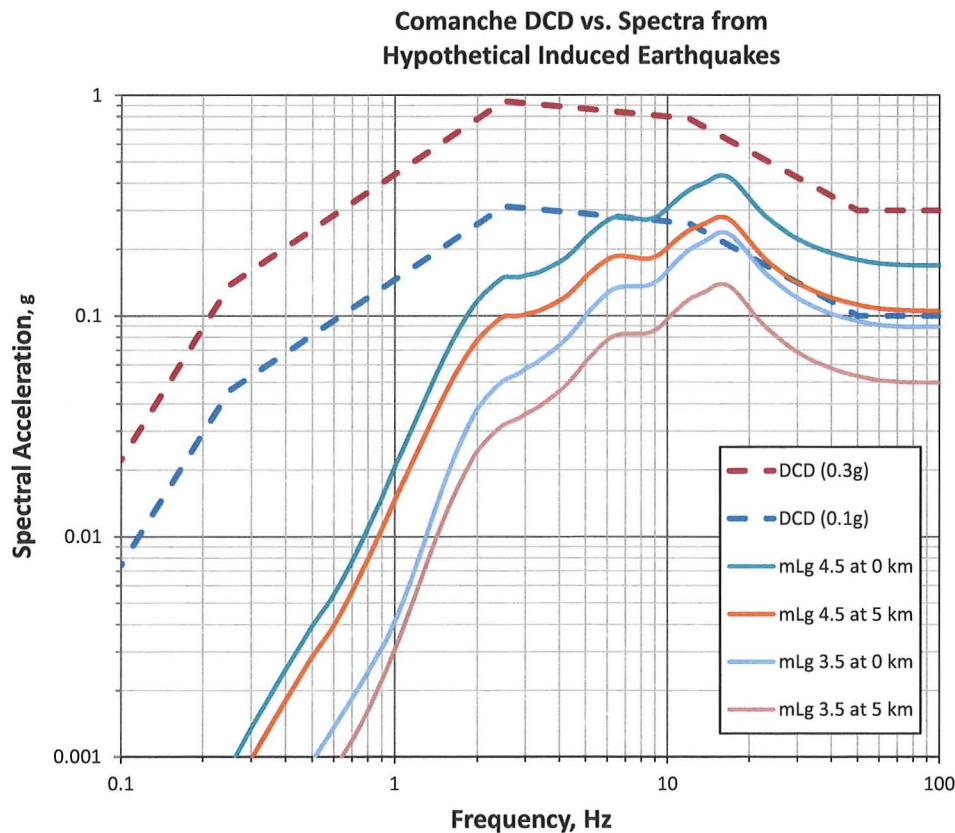
3.0 Discussion

In considering the observed exceedance of the site-specific spectra in Figure 1, it is important to consider that there are a number of conservative elements built into these comparisons, as follows:

1. This is a deterministic analysis, which takes conservatively defined earthquake scenarios as its starting point, and the DCD spectra are included only for the sake of reference. Therefore, exceedance of the 0.1g DCD by these hypothetical earthquakes has no licensing implications. In particular, these exceedances are acceptable and there is no impact on the FIRS or on the GMRS.
2. There is ample evidence that motions from small-magnitude earthquakes are less damaging to nuclear structures than motions from larger earthquakes with the same ground-motion amplitude at high frequencies. This is the motivation for the introduction of the CAV filter (EPRI and DOE, 2005) and for the endorsement of the CAV filter in Regulatory Guide 1.208. Although this study did not perform an analysis in terms of CAV to demonstrate it, it is anticipated that the ground motions from these hypothetical earthquakes have lower damage potential than the motions associated with the 0.1g

DCD spectrum. Therefore, it is anticipated that these hypothetical ground motions have no structural impact.

3. The rock ground-motion equations may over-estimate the motions at the low magnitudes considered in these calculations, as has been observed recently with the NGA equations in California (Chiou and Young, 2010). Although the EPRI (2004) equations rely mostly in Random Vibration Theory (RVT) methods, which are expected to be accurate for small magnitudes, these equations were not fit to magnitudes in this range and it is likely that they over-estimate the motions for magnitudes below 5.
4. There is some evidence that earthquakes induced by natural-gas operations have lower values of stress drop than tectonic earthquakes. For instance, the M 4.7 2011 Arkansas earthquake has been inferred as having a very low stress drop (Mueller et al., 2011). If this is the case, induced earthquakes have less energy at high frequencies than tectonic earthquakes of the same magnitude.



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4.0 Results and Conclusions

Results from the 18-month period of monitoring for earthquakes near the CPNPP and from the compilation of well-documented injection-induced earthquakes indicate that injection-induced earthquakes near CPNPP are likely to have magnitudes lower than **M** 3.5 and occur at distances of 5 km or more.

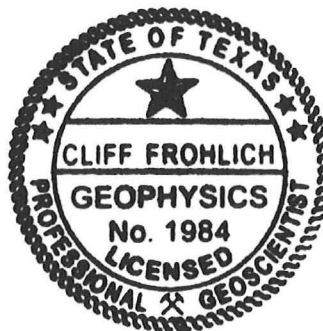
Ground-motion calculations for the above magnitude-distance combination and for more severe combinations (labeled Worst Case) indicate that some of these exceed the 0.1g DCD spectrum at high frequencies. These exceedances are not a source of concern because the associated motions have low damage potential and because there are a number of conservative elements in this deterministic analysis. Therefore, should an induced earthquake occur near the CPNPP, these results show that it is unlikely to be damaging.

5.0 References

- Chiou, B., and R. Youngs (2010). Ground-Motion Attenuation Model for Small-To-Moderate Shallow Crustal Earthquakes in California and Its Implications on Regionalization of Ground-Motion Prediction Models. *Earthquake Spectra* 26, 907 (2010)
- EPRI(2004). CEUS Ground Motion Project, Model Development and Results. Report No. 1008910. Electric Power Research Institute: Palo Alto, CA, 2004.
- EPRI (2006). Program on Technology Innovation: Truncation of the Lognormal Distribution and Value of the Standard Deviation for Ground Motion Models in the Central and Eastern United States. Report No. 1014381. Electric Power Research Institute: Palo Alto, CA, 2006.
- Mueller, C., Cramer, C., and Toro, G. Review of final databases for CENA and other SCRs. NGA-East SSHAC Workshop 2, Oct. 11-13 2011. http://peer.berkeley.edu/ngaeast/wp-content/uploads/2011/10/Tu_PM_1_Cramer_CENA-Database-Status.pdf (Accessed 10/24/2011; see slide 14)
- Rathje, E.M., and M.C. Ozbey (2006). Site-Specific Validation of Random Vibration Theory-Based Seismic Site Response Analysis. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol 132, No.7, July.

Search for Small (M2-M3) Earthquakes Near the Comanche Peak Nuclear Power Plant Using 18 Months of Data Recorded at Four Nearby Temporary Seismograph Stations

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24 October 2011

Abstract: This report describes a search for small earthquakes (M2 – M3) that may have occurred near the Comanche Peak Nuclear Power Plant (CPNPP) between January 2010 and June 2011. During this interval three-component broadband digital seismic data was available from four nearby seismograph stations operated as part of the National Science Foundation's EarthScope program. During the study period only a single earthquake was identified within 35 km of the CPNPP; a very well-recorded M2.3 earthquake that occurred about 10 km WNW of the CPNPP on 23 November 2010 at 1959. For this earthquake, the preferred epicenter at 32.334°N, 97.895°W was situated within 5 km of several injection wells. The closest well at a distance of 1 km from the epicenter injects at a depth of 1.6 km into the Barnett Shale formation; here injection rates have been ~100,000 barrels/month between 2007 and 2010. The highest rates were at a well at a distance of 4 km that injects at a depth of 2.9 km into the Ellenburger Formation; injection rates were variable but were ~150,000 barrels/month between 2007 and 2010, and for one month in 2009 as high as 550,000 barrels. An analysis of earthquakes in the Fort Worth Basin that were probably induced by the disposal of frack fluids finds that their magnitudes are small (M3.3 or less) and, where depth information is available, their focal depths appear to be at or slightly below the depths of injection. Thus future induced earthquakes near the CPNPP are likely to have magnitudes of 3.5 or smaller, and focal depths of 2-5 km.

Search for Small (M2-M3) Earthquakes near the Comanche Peak Nuclear Power Plant Using 18 Months of Data Recorded at Four Nearby Temporary Seismograph Stations

I. Introduction

This report describes a search for small, regional earthquakes near the Comanche Peak Nuclear Power Plant (CPNPP). This involved analyzing 18 months of broadband digital seismic data collected at four seismograph stations surrounding the Comanche Peak Nuclear Site (Figure 1 and Table 1). These four stations form a rectangle with CPNPP lying approximately at the rectangle center, ~50 km distant from each of the stations.

These four seismic stations are components of the USArray Transportable Array, funded as part the National Science Foundation's (NSF) EarthScope program (see <http://www.usarray.org/researchers/obs/transportable>). The USArray Transportable Array consists of ~400 stations, first deployed in 2004 on a 70-km grid, and covering a 500-km-wide swath in the westernmost U.S extending between the southern and northern US borders. Each year the westernmost 200 of the stations are moved eastward, so that the entire U.S. will have been covered by 2013. The Transportable Array is currently deployed in Texas (Figure 2). The four stations analyzed herein were all operating by the end of 2009, and all but WHTX are scheduled to move eastward in October 2011. This report describes a thorough analysis of all data collected between 1 January 2010 and 30 June 2011.

Two questions motivate this analysis:

- 1.) In the vicinity of the CPNPP, how often do small earthquakes occur that are not reported by the National Earthquake Information Center (NEIC)? Prior to the deployment of the Transportable Array (TA), there were high-quality seismograph stations at only about six sites in Texas, and thus most regional earthquakes smaller than about M3.5 were unlocatable. The NEIC does not routinely use Transportable Array data for locations; moreover, it only occasionally reports earthquakes having magnitudes smaller than M3.0. Thus the presence of Transportable Array stations makes it feasible to search for regional earthquakes with magnitudes between M2.0 and M3.0. Our search focuses on epicenters within about 125 km of the CPNPP.
- 2). Are small earthquakes near the CPNPP associated with the disposal of frack fluids in injection wells? The CPNPP lies within the Fort Worth Basin and overlies the Barnett Shale where thousands of natural gas wells have been drilled since about 2000 (Montgomery et al., 2005). Typically these

wells undergo hydrofracture (or ‘fracking’) to enhance permeability, and frack fluids return to the surface as gas is produced. The frack fluids are then pumped into a deep well for disposal. Although there is no credible evidence that fracking wells or producing natural gas causes earthquakes in the Fort Worth Basin, earthquakes have occurred there near disposal wells (Frohlich et al., 2010; 2011; Howe et al., 2010). Thus, this study will identify local earthquakes, and compare their epicenters with the locations of active injection wells (Figure 1) as reported by the Texas Railroad Commission, the state agency tasked with monitoring injection and petroleum production activity.

Section II of this report describes the analysis of seismic data at the four stations, including procedures for identifying and locating local earthquakes. Section III presents results concerning local and regional seismicity. Section IV summarizes sources of information concerning injection wells near the CPNPP. Section V discusses the characteristics of induced earthquakes in the northeastern Texas, focusing especially on activity that has occurred or may occur near the CPNPP.

II. Data and Methods

IIA. Obtaining Seismogram Data and Preprocessing

The four USArray Transportable Array stations surrounding the CPNPP were stations 134A, 135A, 234A, and WHTX (Figure 1 and Table 1). All four were nominally operational for the 18-month period 1 January 2010 through 30 June 2011. All USArray data are publicly available at no cost from the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC; see <http://www.iris.edu/data/seismograms>) in Seattle, Washington. In this study I used the Seismic Analysis Code (SAC; see Goldstein et al., 2003) to manipulate, filter, and view data, and to pick phases arrival times when appropriate.

To assess the properties of small local earthquakes at these stations, I obtained and evaluated three-component broadband digital seismograms for known local earthquakes (Table 2). An M2.1 earthquake reported by the NEIC that occurred on 12 Nov 2010 at 0903 is likely to have properties representative of the earthquakes that are the target of this study. The NEIC reported a location 52 km east of the CPNPP, about 35 km north of WHTX and 31 km south of 135A. Visual inspection and spectral analysis indicated the seismograms were dominated by microseisms and other longer-period (> 3 sec) noise (see Figure 3). However, body wave phases for the 12 Nov 2010 earthquake were clearly visible at all stations after applying a bandpass filter with corners at 1 Hz and 10 Hz. Inspection indicated that the vertical (Z-component) records were less noisy than the N- or E-components.

Thus, for stations 134A, 135B, 234A, and WHTX, I downloaded broadband Z-component data from the IRIS DMC for the entire 1 Jan 2010 through 30 June 2011 period. Then I used SAC to bandpass filter the data with corners at 1Hz and 10 Hz, 4

poles. For the study period there were no data gaps longer than one hour except at station 134A, for which there was a 5-day data gap in May 2011.

IIB. Processing to Identify Candidate Seismic Phase arrivals

To identify potential seismic phase arrivals, I applied a filter that compared the ratio of the signal short-term average (STA) and long-term-average (LTA) [STA interval: 4 sec; LTA interval: 3600 sec]. Using this filter I identified onset times and durations for phase candidate intervals when: (a) the ratio STA/LTA rose above 2.0, defining the onset of the interval; (b) the ratio STA/LTA exceeded 2.0 for at least 10 sec; (c) the STA/LTA exceeded 5.0 at some point before the STA/LTA fell below 2.0, defining the end of the interval.

To identify phase arrivals of potentially locatable earthquakes, I compared the times of phase candidate intervals at the four seismic stations (Table 3), and compiled a list of intervals that overlapped or were separated by a near-overlap of 30 seconds or less. This produced 672 intervals that overlapped or near-overlapped at three or more of the seismic stations. Phase arrivals at a minimum of three stations are required to locate an earthquake.

Of course, one would anticipate that many of these phase candidate intervals would correspond to known earthquakes occurring far distant from the CPNPP. For example, the study period included 11 March 2011 when one of the largest earthquakes in history (M9.0) occurred in Japan. This quake and its aftershocks were about 90° distant from the CPNPP.

Thus, I compared phase candidate interval times with predicted phase arrival times for earthquakes reported by the NEIC. The comparison list included all earthquakes reported by the NEIC within 500 km of the CPNPP (197 earthquakes), and all events of M4.6 and greater at all distances (11563 earthquakes). Arrival times were determined from the IASPEI travel-time tables (Kennett, 1991) for P, PP, and PKP phases in appropriate distance intervals. Of the 672 3-or-more-station overlap intervals, 399 apparently corresponded to NEIC-reported earthquakes with epicenters outside the area of interest in this study (Figures 4-6). The remaining 273 3-or-more-station overlap intervals did not correspond to any known distant earthquake.

IIC. Identification and Location of Local Seismic Events

The next phase of the analysis required visually inspecting actual seismograms to identify arrivals resembling seismograms from local events. For this I used SAC software; I visually inspected arrivals for the 273 3-or-more-station overlap intervals, as well as ~160 arrivals associated with NEIC-reported earthquakes, especially where their residuals with respect to onset interval times were greater than a few seconds. Many of these candidate events were clearly not local earthquakes, as their phase arrivals resembled known teleseismic earthquakes,

regional earthquakes in Oklahoma or the Texas Panhandle, or were simply noise signals coincident in time on three stations.

However, for 54 remaining events with arrivals resembling local events, I downloaded all three components (Z, N, and E) of broadband digital data from the IRIS DMC. Then, using the SAC routine PLOTPK I picked arrival times for P and S phases, assigning a quality factor of 1 to 4 to each picked phase. Quality factors of 1 were for impulsive phases where arrival times were identifiable to ~0.1 sec; quality factors of 4 were for highly uncertain picks which may or may not correspond to the phase of interest.

To locate candidate earthquakes I used the TexFlex location program (Frohlich, 1993). This utilizes a conventional location method that fits arrival times to a user-supplied velocity model using weighted iterative least squares. The velocity model was the flat-layered structure measured at the Trigg well on the Dallas-Fort Worth DFW airport (Geotechnical Corporation, 1964) and used by Frohlich et al., (2010; 2011) to locate earthquakes that occurred in Dallas-Fort Worth. Because the present study utilized stations at greater distances than the Frohlich et al. studies, I added a mantle layer with velocity of 8.0 km/sec for depths exceeding 17.9 km (Table 4).

III. Results Concerning Local and Regional Seismicity

IIIA. Regional Earthquake Locations – Distances of 35-125 km from CPNPP

Many of the 54 events with arrivals resembling local events were not of interest for this study. I was unable to locate several events because reasonable-quality body wave arrivals couldn't be identified at three or more stations. In addition I found credible locations for a number of events but these locations were situated more than 125 km from the CPNPP (mostly in Oklahoma). There were also six epicenters in Jack, Wise, and Clay Counties, about 100-125 km from the CPNPP, and five epicenters in Denton County, about 100 km from the CPNPP (Figure 7 and Table 5).

There were 24 events at distances less than 100 km from the CPNPP, including some with epicenters corresponding to sites where earthquakes induced by fluid injection have occurred previously. These included four epicenters near the DFW airport, with apparent locations close to those that occurred in 2008 and 2009 reported by Frohlich et al. (2010; 2011). There were 19 epicenters located in Johnson County. Four of these were effectively identical to those near Cleburne reported by Howe et al. (2010), and the remainder appeared to originate from sites elsewhere in Johnson County.

IIIB. Regional Earthquake Locations – the 23 Nov 2010 Earthquake Near the CPNPP

The event closest to the CPNPP occurred on 23 November 2010 at 1959; this study's preferred location of 32.334°N, 97.895°W places it 10 km WNW of the location of

the CPNPP at 32.299N, 97.795W. The event is clearly recorded with unequivocally identifiable P and S arrivals at all four stations (Figures 8-11). All P and S picks had assigned qualities of 1 or 2. These strong and distinct body wave arrivals, and the absence of large Rg phases (compare with probable quarry blast in Figure 12; see discussion in Section IIIC) both suggest this event is an earthquake, with a focal depth well beneath surface sedimentary layers, probably several km or more.

The quality of the location was excellent. The RMS residual (average difference between observed and calculated travel times) was 0.09 sec for our preferred location using the velocity model of Table 4 and with focal depth fixed at 5 km. The formal uncertainty for the preferred location (see Table 5) was less than one km; considering possible systematic errors, etc., a conservative but realistic estimate of the location uncertainty would be 2-3 km.

To estimate a magnitude for the 23 November 2010 earthquake, I measured the peak-to-peak amplitude A_{PtoP} at all four stations for the six local earthquakes with locations and magnitudes M reported by the NEIC during and shortly before or after the study period (Table 2). I then performed a least-squares fit for these data to the equation:

$$a \log_{10} A_{PtoP} + b \Delta^\circ = M \quad \text{eq. (1)}$$

where A_{PtoP} was velocity amplitude in the units assessed from the SAC data (e.g., Figure 3 and Figures 8-11), and Δ° was the epicenter-to-station distance in degrees. This best-fitting relationship was:

$$0.572 \log_{10} A_{PtoP} + 0.285 \Delta^\circ = M. \quad \text{eq. (2)}$$

For the 23 November 2010 earthquake this gave a magnitude of 2.3.

To determine if other earthquakes, undetected by our procedures described in Section II, had occurred with hypocenters close to the 23 November 2010 earthquake, I performed a cross-correlation between 30 sec of the event's Z-component signal at station 134A and the signal for the entire 1 January 2010 through 30 June 2011 period. This procedure detected no events with a correlation coefficient larger than 0.30. Thus, the 23 November 2010 earthquake appears to be an isolated event.

IIIC. Regional Locations – Probable Quarry Blasts

Three events had locations in Parker County, 30-50 km from the CPNPP. These events possessed very high-amplitude phases at 134A and much smaller amplitudes at the other stations; rotating the horizontal component seismograms at 134A by 65° demonstrated that the large-amplitude arrivals corresponded to but were out-of-phase with similar arrivals on the Z component (Figure 12). This identifies them as Rg phases and allowed the identification of (weak) P and S arrivals. In addition to these three locatable events, there were 16 virtually identical events that were unlocatable because it wasn't possible to identify P or S at three stations (Table 6).

For several reasons these events are probably quarry blasts. First, the presence of dominant Rg phases and weak body-wave phases is indicative of very shallow focal depths and is often associated with quarry blasts (Kafka, 1990). Second, the seismograms possess two separate Rg wave groups; for the earlier-arriving wave group the particle motion is prograde whereas for the later-arriving group the particle motion is retrograde; sources in shallow, very low-velocity sediment layers overlying higher-velocity layers can generate prograde Rg signals (Tanimoto and Rivera, 2005; Malischewsky Auning et al., 2006). Third, all 19 of these virtually identical events had origin times indicating they occurred between 1138 and 1607 hours local time and none occurred on a Saturday or Sunday. Finally, a GoogleMap search of satellite images northeast of station 134A identified several large open-pit quarries (e.g., coordinates: 32.65N, 97.825W; 32.715N, 97.86W); either one of these or another as-yet-unidentified quarry could be the source of these signals.

Other unlocatable events with large amplitude Rg phases at 234A were probably also quarry blasts. I made no effort to find possible quarries responsible for these.

IV. Injection Wells and the Texas Railroad Commission

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 frack 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.

Information concerning wells active since 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. Since the present study is concerned with injection related to gas production in the Barnett Shale, nearly all the data of interest arise from the period since 2004; for this interval the online information is available and presumably complete. Probably because most regulations were instituted prior to the modern computer age when data transfer was by hand, the information archived by the RRC is quite sparse (monthly volumes, dates permits awarded, etc., names and depths of geologic units involved).

Since Texas receives considerable revenue from taxation on oil and gas production, and since the RRC website is used regularly by individuals and companies

researching possible future drilling projects, the design of the RRC database makes it easier to find information about production than injection. Some information, such as the location and permit dates of injection wells, is relatively easy to obtain from the RRC website. Other information, such as the monthly injection volumes, is more troublesome to obtain as it has to be searched on a well-by-well basis.

For this study I obtained locations of all injection wells in the RRC database permitted for injection since 2007 (Figures 1, 13 and 14). This may include some wells that were permitted but where no injection ever occurred, or where the volumes of injected fluid were relatively small. Then, for selected permitted wells closest to the CPNPP (filled squares in Figures 13 and 14) I obtained data concerning monthly injection volumes (Figures 15-17). The monthly injection volume data concerned two groups of wells: six wells about 3-12 km east of the CPNPP and seven about 10-20 km to the west.

V. Induced Earthquakes and the Comanche Peak Nuclear Power Plant

One objective of this study was to obtain a 'snapshot' of seismic activity in the neighborhood of the CPNPP, specifically focusing on events having magnitudes in the M2-M3 range, i.e., smaller than the events routinely reported by the NEIS. To accomplish this I analyzed 18 months of data recorded by four temporary seismic stations surrounding the CPNPP. These four stations were installed as part of the EarthScope USArray Transportable Array program; although they were not installed specifically for this study they effectively formed a 'retrospective network' well designed to evaluate seismicity near the CPNPP.

The analysis of these data allowed me to locate about 30 earthquakes (Figure 7 and Table 5) not reported by the NEIC. Comparison of the amplitudes of selected events with amplitudes of regional NEIC-reported earthquakes demonstrates that the newly found events had magnitudes in the range M1.9-M2.5.

Only one of these events occurred within 35 km of the CPNPP, an earthquake having magnitude M2.3 that occurred on 23 November 2010 at 1959 about 10 km WNW of the plant. This event was exceptionally well recorded; clear P and S phases were visible at all four seismic stations. Our preferred epicenter has a formal uncertainty of less than one kilometer; allowing for possible systematic effects suggests that it is accurate to 2-3 km or better. Our four-station network is inadequate for obtaining accurate focal depths. However, the observation that P and S are strong while Rg is not prominent indicates the focal depth is several kilometers, well below surface sedimentary layers.

A significant observation is that the 23 November 2010 earthquake is situated close to active injection wells (Figure 14). This earthquake's epicenter earthquake is only one kilometer from well 2, which injected ~100,000 barrels of water (BW) in typical months between 2007 and 2010; it is only 4 km from well 4, where injection volumes peaked 550,000 BW during that period (Figure 15). Injection well 2 was

drilled to a depth of 9500 ft (2.9 km) into the Ellenburger formation, the strata that lies directly beneath the Barnett. Injection at well 4 was drilled to 5200 ft (1.6 km) into the Barnett.

It is important to note that these injection volumes are not unusually high either for regional disposal wells or as compared to wells elsewhere in the Fort Worth Basin. Several wells in the east group had monthly injection volumes that often exceeded 400,000 BW/month (Figures 16-17). Similarly, Frohlich et al. (2010; 2011) found that injection volumes of ~300,000 BW/month were fairly typical of wells in both Tarrant County and Johnson Counties, including numerous wells where no earthquakes were reported. Nevertheless, it is notable that both the 2008-2009 DFW and the 2009 Cleburne earthquakes also had epicenters situated within 1-2 km of injection wells. At the DFW well injection volumes were ~300,000 BW/month.

The occurrence of the 23 November 2010 earthquake so close to active injection wells strongly suggests that injection may have induced the earthquake. In this respect it is similar to the majority of regional earthquakes found in this study. There are one or more injection wells within a few km of the earthquake clusters labeled 'DFW', 'Cle', 'JC1', 'JC2, and possibly 'D1' in Figure 7; this represents 27 of the 38 earthquakes listed in Table 5. It is notable that none of these earthquakes has a magnitude exceeding 3.0. The largest Texas earthquake apparently associated with the disposal of frack fluids at an injection well was the M3.3 Dallas-Fort Worth earthquake that occurred on 16 May 2009. Frohlich et al.'s (2010; 2011) preferred depth for the Dallas-Fort Worth earthquakes was 4.4 km, at or slightly below the disposal well depth of 4.2 km. Depths determined for probably-induced earthquakes at Cleburne (Howe et al., 2010), at Denver (Hsieh and Bredehoeft, 1981), and in Arkansas are all also at or somewhat below the depth of injection.

Thus, if the disposal of fluids at injection wells does induce future earthquakes in the vicinity of the CPNPP, the record of past activity suggests that:

- 1) These earthquakes would be small, most likely with magnitudes of 3.5 or less.
- 2) The focal depths would be relatively shallow but at or below the depth of injection. Thus the depths would probably be 3-5 km, but possibly as shallow as 2 km.

References

- Frohlich, C. (1993). *Users Manual for TexFlex-0.5: The Texas Flexible, Practical Program for Locating Seismic Events*, Univ. Texas Institute for Geophysics Technical Rept. No. 128, 64 pp.
- Frohlich, C., C. Hayward, B. Stump and E. Potter (2011). The Dallas-Fort Worth earthquake sequence: October 2008 through May 2009, *Bull. Seismol. Soc. Amer.*, *101*, doi:10.1785/0120100131
- Frohlich, C., E. Potter, C. Hayward and B. Stump (2010). Dallas-Fort Worth earthquakes coincident with activity associated with natural gas production, *Leading Edge*, *29*, 270-275, doi:10.1190/1.3353720.
- Goldstein, P., D. Dodge, M. Firpo and L. Minner (2003). SAC2000: Signal processing and analysis tools for seismologists and engineers, *The IASPEI International Handbook of Earthquake and Engineering Seismology*, edited by WHK Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger, Academic Press, London.
- Geotechnical Corporation (1964). *Deep-Hole Site Report, Trigg No. 1, Dallas County, Texas*, Geotechnical Corporation Tech. Rept. 64-100.
- Howe, A. M., C. T. Hayward, B. W. Stump, and C. Frohlich (2010). Analysis of recent earthquakes in Cleburne, Texas, *Seismol. Res. Lett.*, *81*, 379.
- Hsieh, P. A. and J. S. Bredehoeft (1981). A reservoir analysis of the Denver earthquakes—A case study of induced seismicity, *J. Geophys. Res.*, *86*, 903-920.
- Kafka, A. L. (1990). Rg as a depth discriminant for earthquakes and explosions: A case study in New England, *Bull. Seismol. Soc. Amer.*, *80*, 373-394.
- Kennett, B. L. N. (1991). IASPEI 1991 Seismological Tables. *Terra Nova*, *3*, 122.
doi: 10.1111/j.1365-3121.1991.tb00863.x
- Malischewsky Auning, P. G., C. Lomnitz, F. Wuttke and R. Saragoni (2006). Prograde Rayleigh-wave motion in the valley of Mexico, *Geofisica Int.*, *45*, 149-162.
- Montgomery, S. L., D. M. Jarvie, K. A. Bowker and R. M. Pollastro (2005). Mississippian Barnett shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential, *AAPG Bull.*, *89*, 155-175, doi:10.1306/09170404042.
- Tanimoto, T. and L. Rivera (2005). Prograde Rayleigh wave particle motion, *Geophys. J. Int.*, *162*, 399-405.

Table 1. Locations of seismograph stations used in this study

<i>Station Code</i>	<i>Latitude (°N)</i>	<i>Longitude (°W)</i>	<i>Elevation (m)</i>
134A	32.5729	98.0795	297
135A	32.5573	97.4099	270
234A	32.0040	98.1368	358
WHTX	31.9913	97.4561	190

Table 2. Earthquakes reported by the NEIC between December 2009 and July 2011. In column labeled 'felt', 'F' indicates the earthquake was reported as felt by nearby inhabitants, and the number indicates the Modified Mercalli Intensity. The 'dist' column lists the distance in km from the CPNPP. The NEIC does not routinely use the stations in Table 1 to locate earthquakes, and thus the NEIC epicenters for small earthquakes like these are typically 5-10 km from the true epicenter.

<i>year</i>	<i>mo</i>	<i>da</i>	<i>hrmi</i>	<i>sec</i>	<i>lat</i>	<i>lon</i>	<i>dep</i>	<i>mag</i>	<i>felt</i>	<i>dist</i>
2009	12	05	0530	11.84	32.41	-97.00	5	2.9	3F	75
2010	11	08	0405	56.20	32.26	-97.39	5	2.5	2F	38
2010	11	12	0903	49.79	32.36	-97.25	5	2.1	-F	52
2011	06	12	1651	48.06	32.24	-97.00	5	2.7	4F	75
2011	06	25	0538	53.62	32.44	-97.08	5	2.4	3F	69
2011	07	17	0658	00.04	32.42	-97.08	5	3.0	4F	68

Table 3: Summary of candidate events

<i>Intervals</i>	
4490	At station 134A
4404	At station 135A
47439	At station 234A
4441	At station WHTX
<i>Coincidences</i>	
672	Overlap or near-overlap of intervals at 3 or 4 stations
399	Intervals coincides with P, PP, or PKP arrival from NEIC-reported distant earthquake
~430	Events inspected visually (estimated)
<i>Events identified</i>	
54	Phase arrival times read and relocation attempted
41	Relocation successful
38	Epicenters located within 125 km from CPNPP (Table 5)
23	Rg-dominated events inspected (Table 6)

Table 4. Velocity model used to locate seismic events in this study. The uppermost three layers of this model are based on measurements in the Trigg No. 1 well in Dallas (Geotechnical Corp., 1964). The V_P/V_S ratio assumed for the preferred location of the 2010 November 23 1959 event was 1.7.

<i>Layer</i>	<i>Thickness (km)</i>	<i>P velocity (km/s)</i>
1	0.60	2.9
2	2.15	4.0
3	15.15	6.3
4	1000	8.0

Table 5. Seismic events located within 125 km of the CPNPP. All depths were fixed at 5 km. Key: 'EvID' is an event identification number used for this study; events marked with '*' were reported by the NEIC (see Table 2) and also located in this study; 'y mo da hr mn sec' are event origin time; 'lat long' are latitude and longitude; rms is root-mean square average of residuals; 'ax1 ax2 az' are the lengths in km of principal axes of the uncertainty ellipsoid and the azimuthal orientation; 'sumWt' is the sum of weights of P and S readings; 'gap' is the azimuthal gap in degrees; 'lcID' is a location method identifier used to record different parameterizations used for different location efforts; 'mag' is the magnitude as determined from eq. (2) for selected events.

Event Near CPNPP																	
EvID	y	mo	da	hr	mn	sec	lat	lon	dep	rms	ax1	ax2	az	smWt	gap	lcID	mag
391	2010	11	23	19	59	54.05	32.334	-97.895	5	0.09	0.55	0.73	340	7.00	115.1	E391	2.3
Johnson County Group																	
EvID	y	mo	da	hr	mn	sec	lat	lon	dep	rms	ax1	ax2	az	smWt	gap	lcID	mag
* 1	2009	12	5	5	30	13.96	32.351	-97.220	5	0.46	0.69	1.13	360	2.50	247.0	27Ag	2.9
2	2010	1	2	8	6	47.98	32.427	-97.284	5	0.46	1.01	1.52	315	5.25	237.7	27Ag	2.1
39	2010	1	27	9	20	23.57	32.468	-97.273	5	0.36	1.27	0.61	27	4.25	289.7	27Ag	1.9
183	2010	5	25	4	35	47.02	32.458	-97.284	5	0.48	1.01	1.24	315	4.50	244.3	27Ag	2.1
337	2010	9	30	10	48	44.25	32.289	-97.409	5	0.70	2.42	3.27	5	7.00	187.9	27Ag	2.2
354	2010	10	15	11	36	2.92	32.464	-97.273	5	0.33	1.02	0.64	23	5.00	249.4	27Ag	
*377	2010	11	8	4	5	54.79	32.291	-97.412	5	0.62	2.12	3.01	8	6.25	186.8	27Ag	2.5
*378	2010	11	8	7	29	48.60	32.307	-97.398	5	0.77	2.39	2.63	31	5.00	191.3	27Ag	2.1
383	2010	11	12	9	3	51.29	32.292	-97.410	5	0.67	2.27	2.75	4	6.25	187.2	27Ag	2.1
620	2011	5	23	3	57	26.88	32.420	-97.154	5	0.47	0.81	0.80	33	4.50	268.4	27Ag	
629	2011	6	1	21	0	24.34	32.287	-97.401	5	0.70	2.29	3.04	5	6.75	190.5	27Ag	2.3
632	2011	6	3	20	27	56.07	32.281	-97.289	5	0.51	1.24	1.52	357	7.25	226.4	27Ag	
636	2011	6	7	0	27	56.93	32.434	-97.288	5	0.57	1.29	1.41	341	7.00	237.5	27Ag	2.2
641	2011	6	7	21	51	22.18	32.440	-97.266	5	0.55	1.17	1.30	351	7.00	245.9	27Ag	2.4
642	2011	6	7	23	35	19.06	32.441	-97.272	5	0.51	1.21	1.30	336	8.00	244.1	27Ag	2.4
651	2011	6	7	21	47	40.20	32.434	-97.281	5	0.40	0.68	0.73	330	5.50	239.9	27Ag	2.2
*655	2011	6	12	16	51	48.92	32.511	-97.104	5	0.63	1.68	1.08	335	8.00	289.7	28Au	2.7
*656	2011	6	25	5	38	51.93	32.510	-97.114	5	0.57	1.67	1.02	345	7.50	288.5	28Au	2.4
*657	2011	7	17	6	58	0.03	32.517	-97.114	5	0.57	1.69	1.01	344	7.50	289.6	28Au	3.0
DFW Group																	
EvID	y	mo	da	hr	mn	sec	lat	lon	dep	rms	ax1	ax2	az	smWt	gap	lcID	mag
185	2010	5	26	5	54	55.99	32.886	-97.142	5	0.94	1.91	3.45	15	5.75	208.3	27Ag	
372	2010	11	1	11	1	15.36	32.845	-97.127	5	0.96	2.14	4.17	26	6.75	210.4	27Ag	
392	2010	11	23	20	2	25.19	32.808	-97.028	5	1.93	10.94	10.02	29	4.00	148.1	27Ag	
408	2010	12	13	7	48	13.62	32.869	-97.049	5	1.07	5.41	7.28	7	7.75	152.3	27Ag	
Denton County Group																	
EvID	y	mo	da	hr	mn	sec	lat	lon	dep	rms	ax1	ax2	az	smWt	gap	lcID	mag
387	2010	11	20	15	35	57.61	33.160	-97.302	5	1.48	6.32	9.72	9	5.00	172.9	27Ag	2.3
389	2010	11	21	9	24	12.40	33.149	-97.290	5	1.75	7.09	11.05	2	4.50	177.3	27Ag	2.1
393	2010	11	24	0	49	23.89	33.163	-97.297	5	1.25	6.42	9.13	2	7.00	124.5	27Ag	2.4
406	2010	12	11	2	29	50.31	33.181	-97.303	5	1.27	5.63	8.59	12	5.75	170.5	27Ag	2.3
410	2010	12	13	21	7	32.52	33.167	-97.309	5	1.15	5.97	8.87	14	7.75	120.4	27Ag	2.5
Jack, Wise, Clay Counties Group																	
EvID	y	mo	da	hr	mn	sec	lat	lon	dep	rms	ax1	ax2	az	smWt	gap	lcID	mag
25	2010	1	18	18	50	14.97	33.282	-98.061	5	1.25	3.08	5.19	13	4.25	230.8	27Ag	
273	2010	7	30	10	31	11.63	33.446	-97.848	5	1.76	3.20	5.26	4	8.50	246.0	27Ag	
280	2010	8	3	15	32	13.04	33.275	-98.035	5	0.97	1.73	3.75	22	4.00	222.3	27Ag	
425	2010	12	29	4	32	42.79	33.404	-97.681	5	0.79	1.49	8.26	9	2.75	330.3	27Ag	
526	2011	3	21	19	19	1.80	33.292	-97.743	5	1.32	5.59	7.97	330	4.00	145.6	27Ag	
612	2011	5	16	21	7	7.59	33.244	-97.860	5	1.44	5.51	21.43	357	3.50	171.0	27Ag	
Parker County Group (near Station 134A; see also Table 6)																	
EvID	y	mo	da	hr	mn	sec	lat	lon	dep	rms	ax1	ax2	az	smWt	gap	lcID	mag
776	2011	5	17	18	28	54.74	32.621	-97.837	5	0.63	1.60	2.67	21	1.75	203.1	27Ag	
781	2011	5	25	19	34	41.50	32.579	-97.887	5	0.68	2.06	2.96	350	2.00	185.0	27Ag	
786	2011	6	1	17	37	5.88	32.684	-97.848	5	0.65	1.27	1.00	350	2.50	228.8	Ray1	

Table 6. Probable explosions or quarry blasts

Near Station 134A (Parker County Group)

<i>EvID</i>	<i>y</i>	<i>mo</i>	<i>da</i>	<i>hr</i>	<i>mn</i>	<i>GMT</i>	<i>local</i>	<i>day</i>
							<i>hr mn</i>	
140	2010	4	13	19	58		14 58	Tues
187	2010	5	26	19	25		14 25	Wed
222	2010	6	28	20	43		15 43	Mon
233	2010	7	8	18	37		13 37	Thur
241	2010	7	16	18	9		13 0	Fri
256	2010	7	22	19	30		14 30	Tues
281	2010	8	3	19	26		14 26	Tues
343	2010	10	7	18	9		13 9	Thur
375	2010	11	4	21	7		16 7	Thur
385	2010	11	16	19	8		14 7	Tues
403	2010	12	3	17	38		11 38	Tues
572	2011	4	21	18	25		13 25	Thur
578	2011	4	26	19	40		14 40	Tues
588	2011	4	28	17	15		12 15	Thur
640	2011	6	7	18	29		13 39	Tues
771	2011	5	4	19	27		14 27	Wed
776	2011	5	17	18	28		13 28	Tues
781	2011	5	25	19	34		14 34	Wed
786	2011	6	1	17	37		12 37	Wed

Near Station 234A

<i>EvID</i>	<i>y</i>	<i>mo</i>	<i>da</i>	<i>hr</i>	<i>mn</i>	<i>hr mn</i>	<i>day</i>
801	1020	4	7	17	4	12 4	Wed
806	2010	6	23	19	40	14 40	Wed
811	2010	7	9	19	2	15 2	Fri
816	2010	7	23	16	16	11 16	Fri
821	2010	9	27	18	25	13 25	Mon

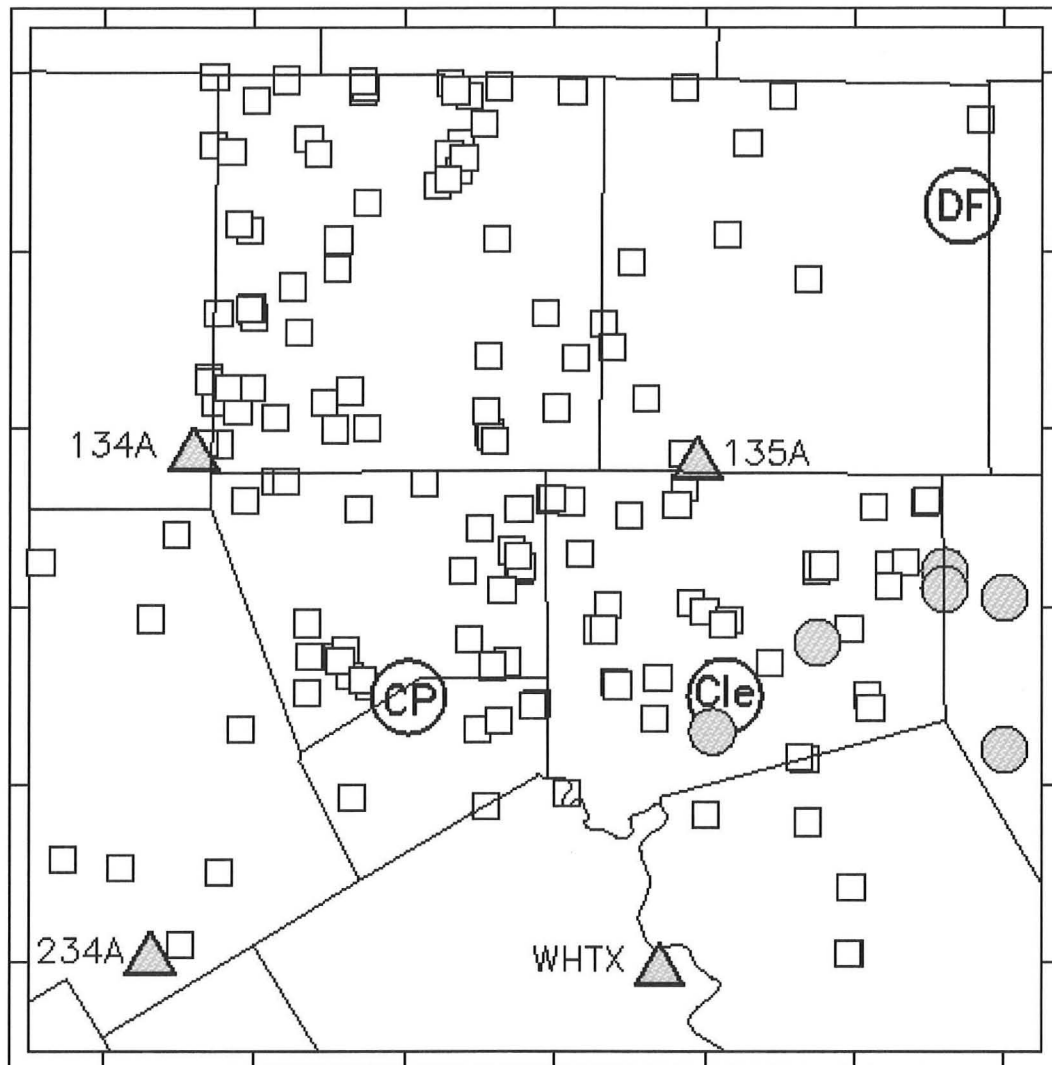


Figure 1. Map showing the Comanche Peak Nuclear Power Plant (labeled CP) and the four seismograph stations (triangles) providing data analyzed for this report. Squares are locations of injection wells active since 2007 as reported by the Texas Railroad Commission. Filled circles indicate NEIC-reported locations of earthquakes occurring during the study period (Table 2); labeled open circles shows the locations of earthquakes reportedly induced by fluid injection near Dallas-Fort Worth (DF) and Cleburne (Cle). Solid lines are county lines.

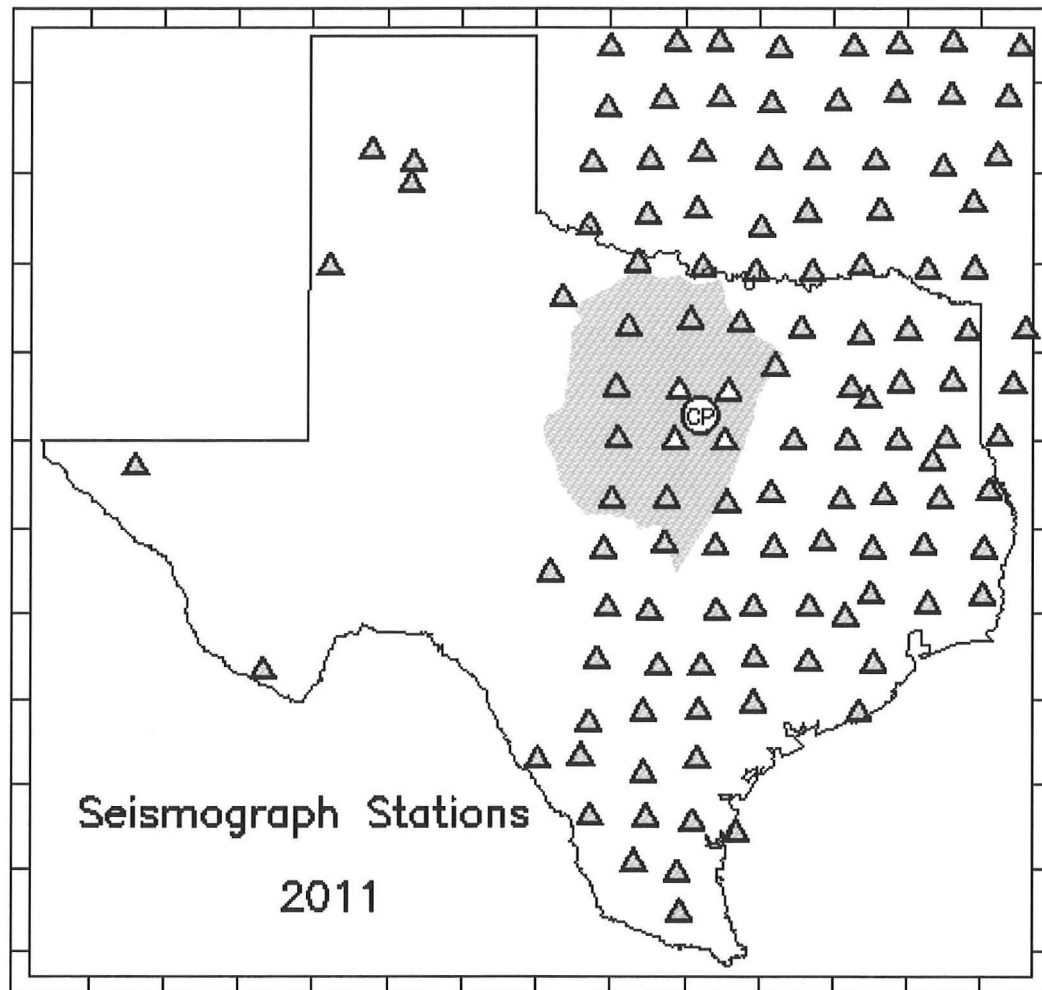


Figure 2. Regional seismograph stations (triangles) operating as of August 2011; open symbols are stations providing data analyzed in this study. Most of these stations are part of the USArray Transportable Array; the ~400 stations of this array are deployed for two years on a 70 km grid, with half of the stations moving eastward each year. Shaded area is extent of Barnett Shale, which has been heavily developed for natural gas production since about 2000.

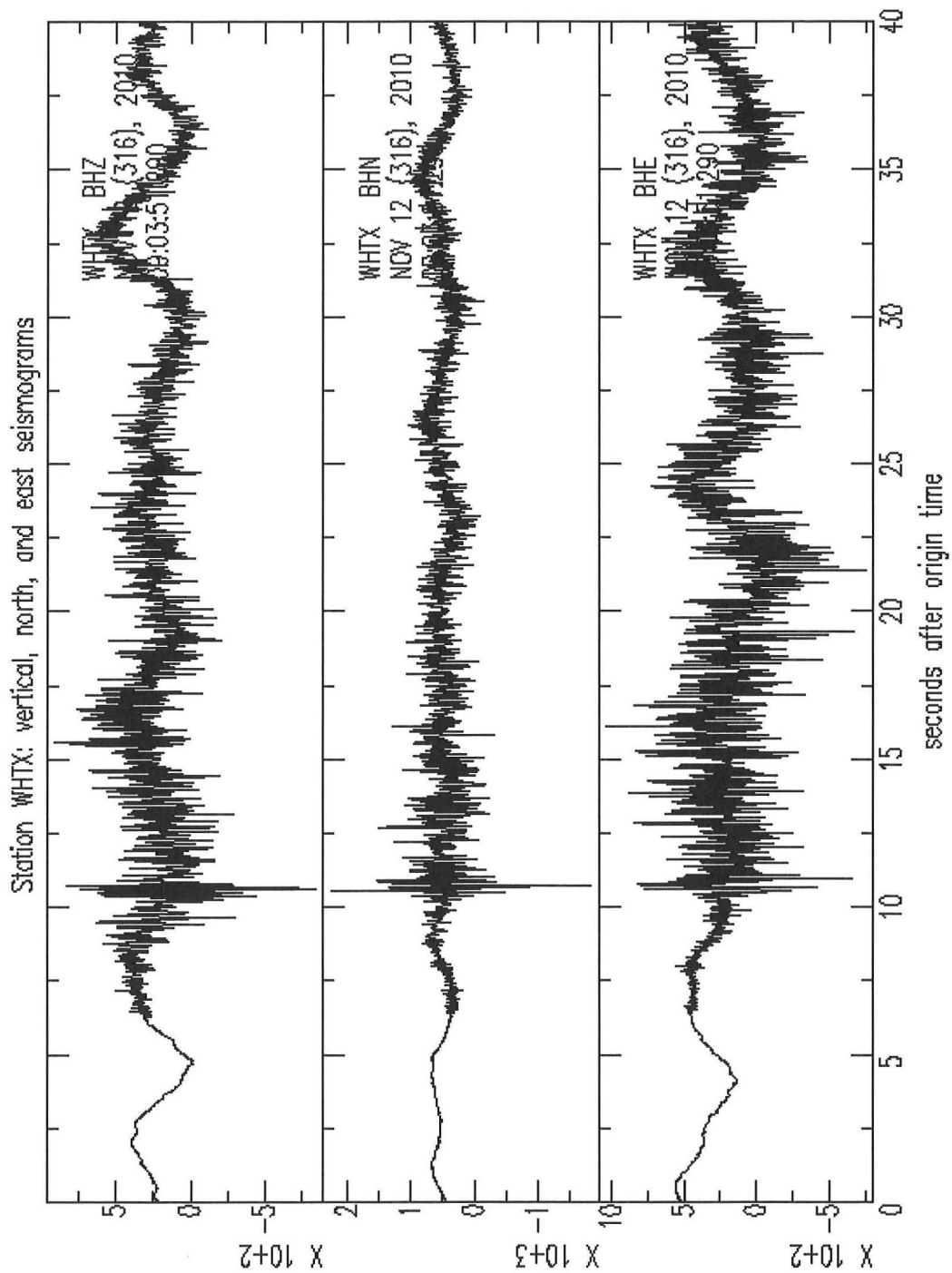


Figure 3. Seismograms at station WHTX for the 12 Nov 2010 0903 earthquake, located by the NEIC 52 km from the CPNPP. The three panels show the Z (top), N (center) and E (bottom) components. With a NEIC-assigned magnitude of M2.1, the character, duration, and amplitude of these signals are representative of the local earthquakes of interest in this study.

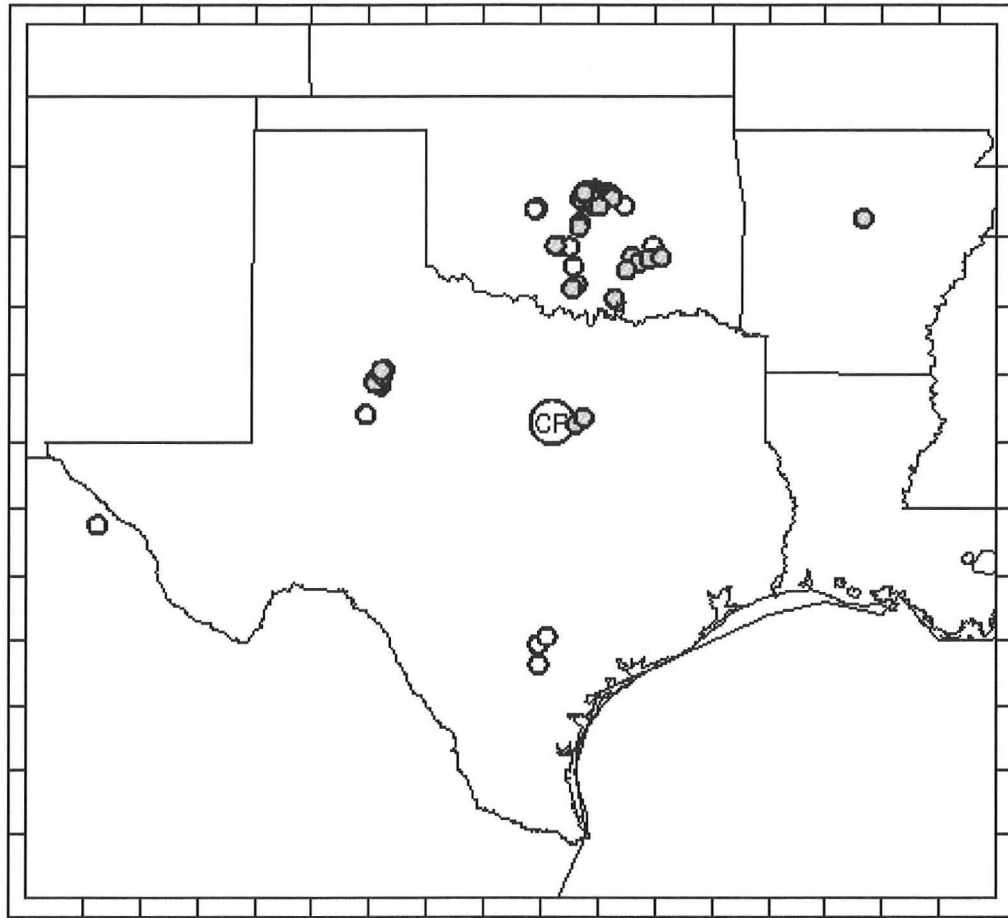


Figure 4. NEIC-reported locations for regional earthquakes producing phase arrivals identifiable at 3 stations (open circles) and all four stations (filled circles) among stations 134A, 135A, 235A and WHTX (see Figure 1).



Figure 5. NEIC-reported locations for earthquakes within 90° of the CPNPP, and producing phase arrivals identifiable at 3 stations (open circles) and all four stations (filled circles).

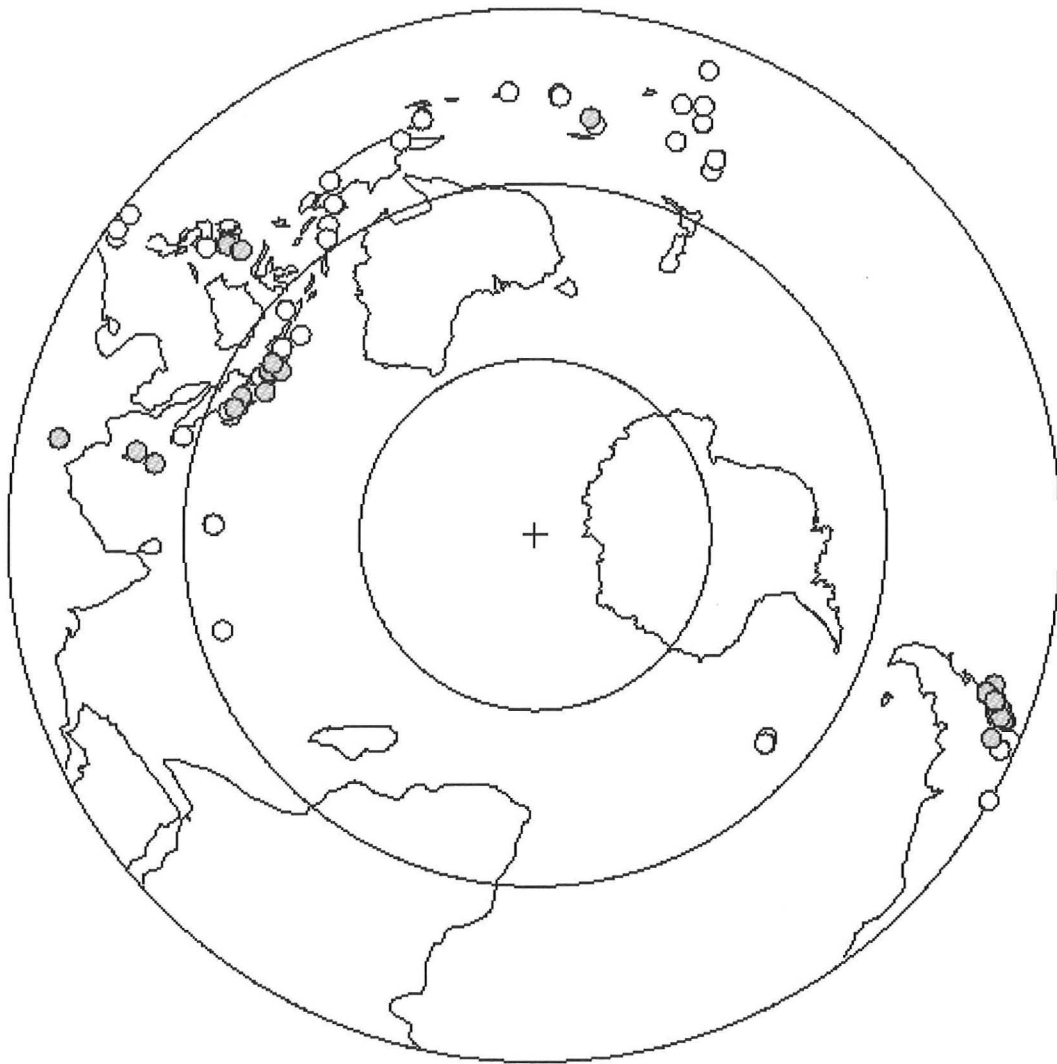


Figure 6. NEIC-reported locations for earthquakes between 90° and 180° from the CPNPP, and producing phase arrivals identifiable at 3 stations (open circles) and all four stations (filled circles).

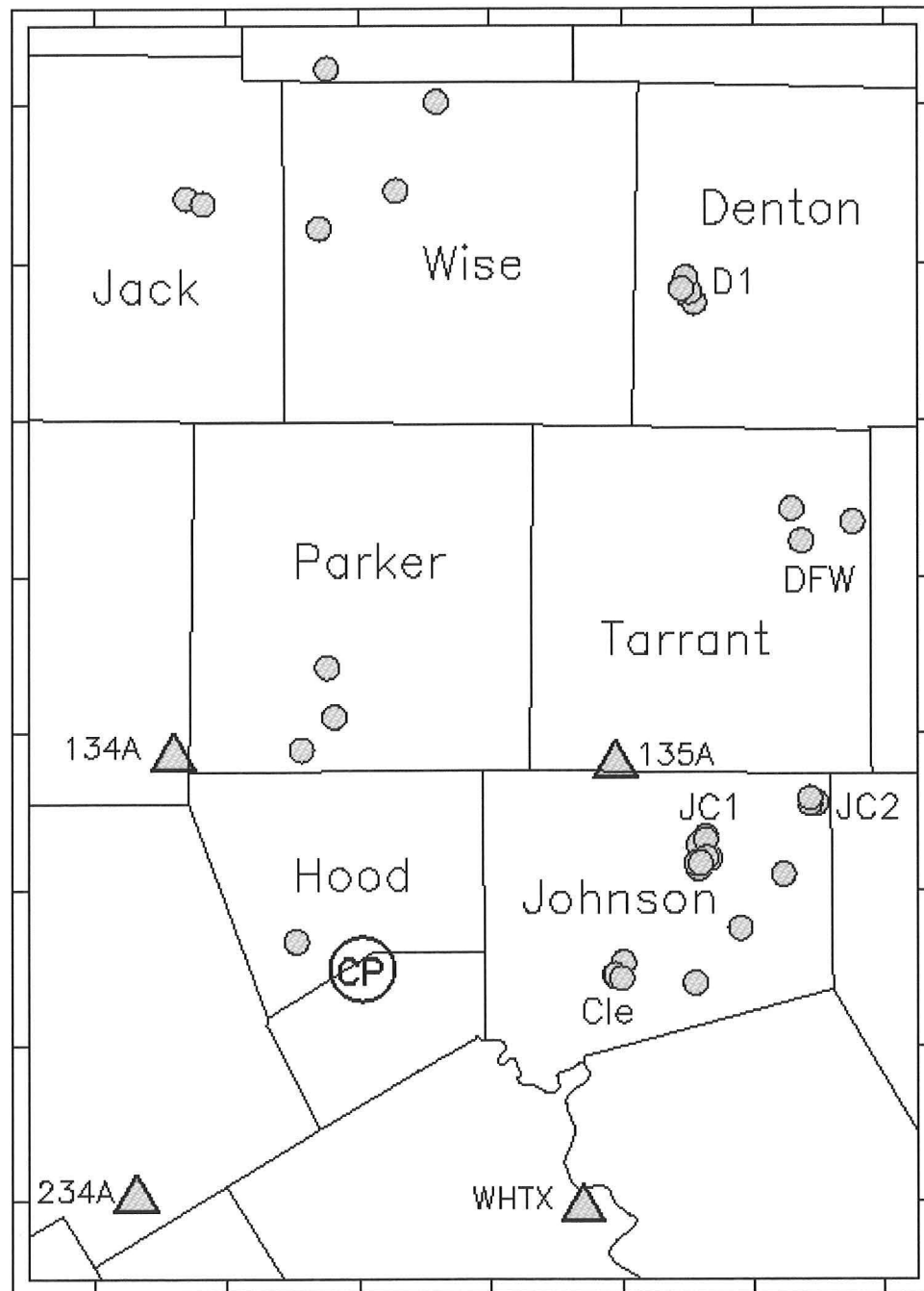


Figure 7. Locations of seismic events determined in this study. The earthquake of 2010 Nov 23 at 1959 is of special interest as it lies about 10 km from the CPNPP. The clusters labeled 'DFW', 'Cle', 'JC1', 'JC2' and 'D1' are groups of earthquakes occurring near known injection wells (see text).

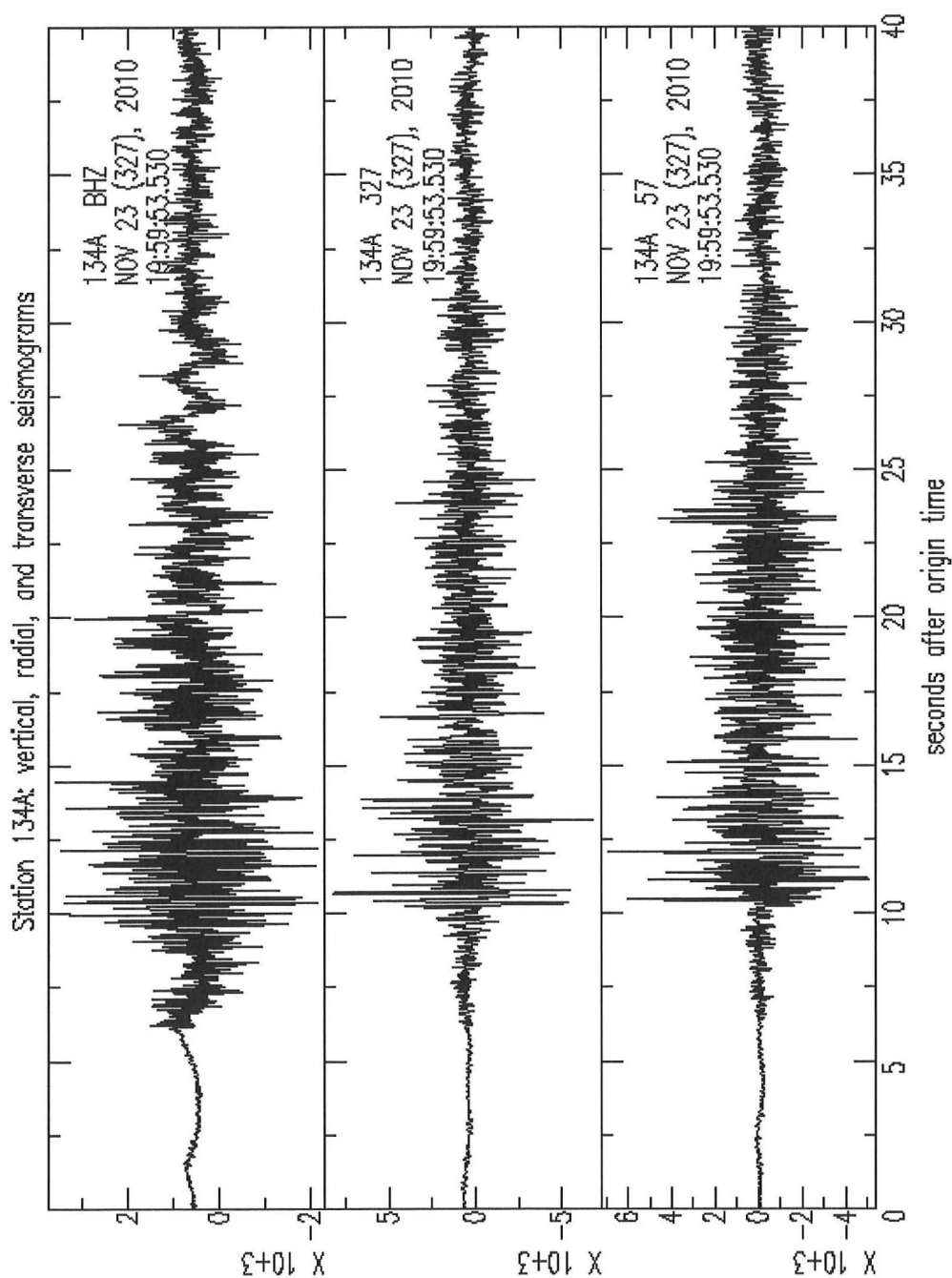


Figure 8. Seismograms at station 134A for the earthquake of 2010 Nov 23 at 1959 near the CPNPP. The top panel is the Z-component; horizontal components are rotated to show radial (middle panel) and tangential (bottom panel) components.

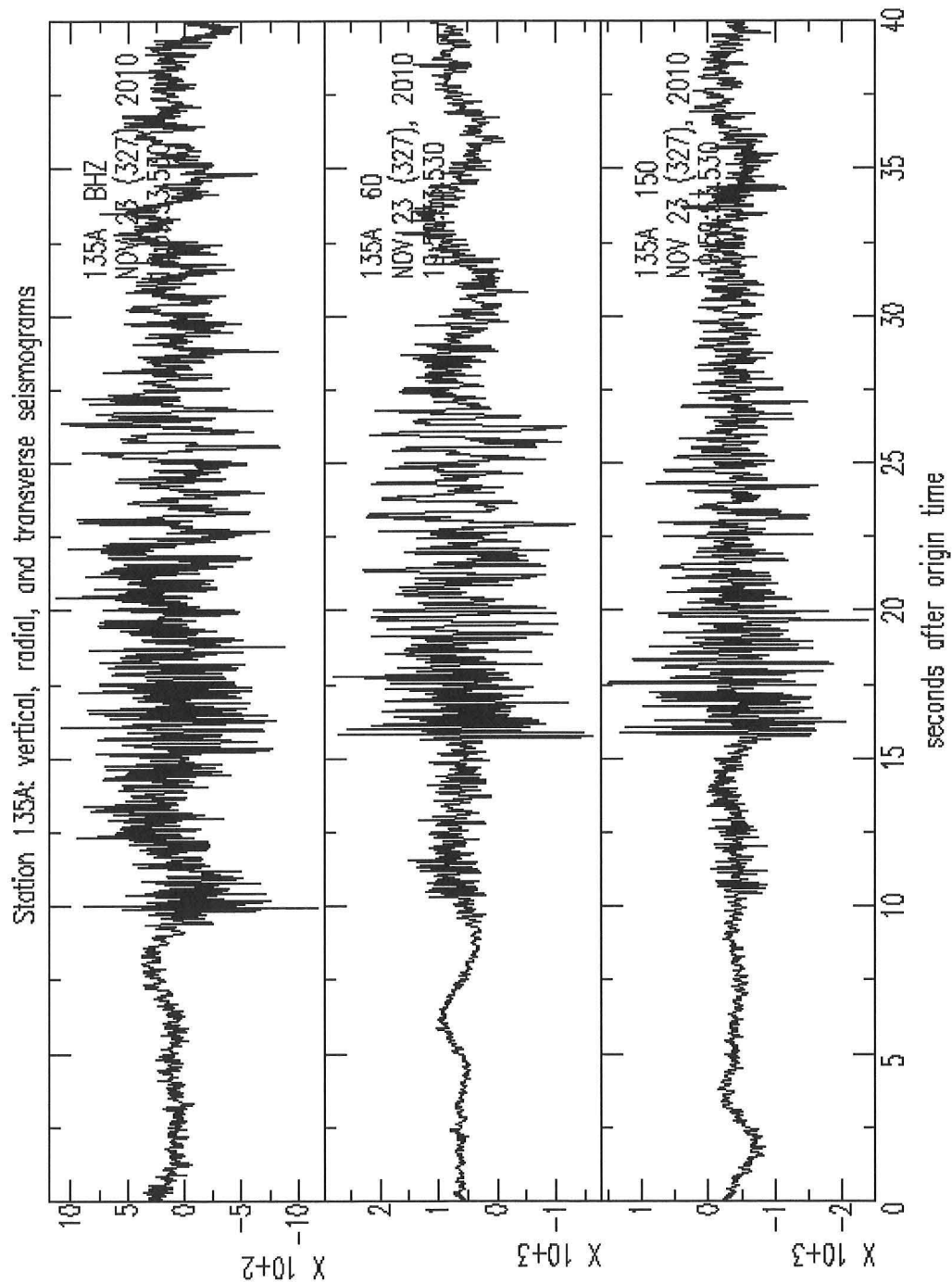


Figure 9. Seismograms at station 135A for the earthquake of 2010 Nov 23 at 1959 near the CPNPP. The top panel is the Z-component; horizontal components are rotated to show radial (middle panel) and tangential (bottom panel) components.

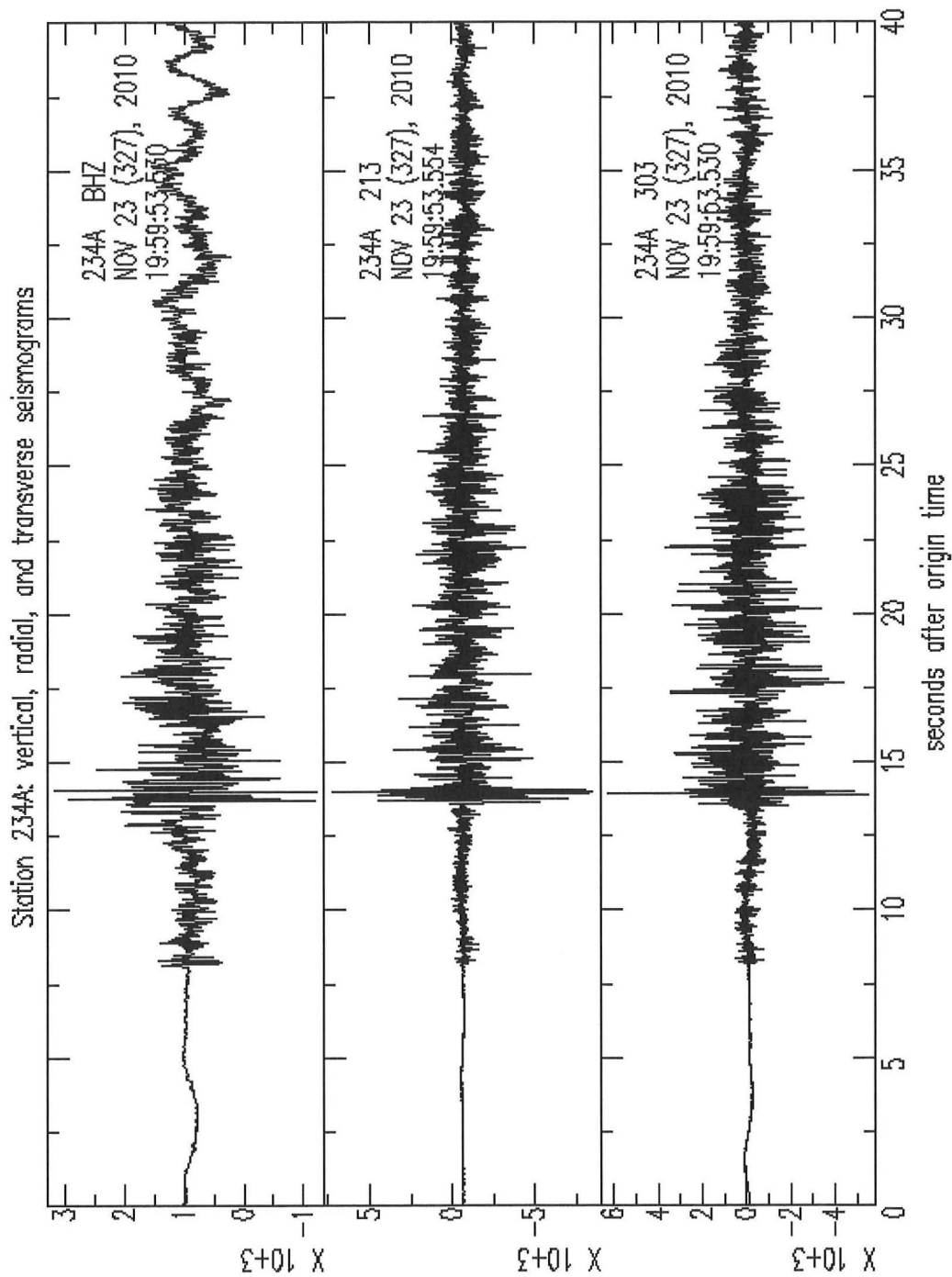


Figure 10. Seismograms at station 234A for the earthquake of 2010 Nov 23 at 1959 near the CPNPP. The top panel is the Z-component; horizontal components are rotated to show radial (middle panel) and tangential (bottom panel) components.

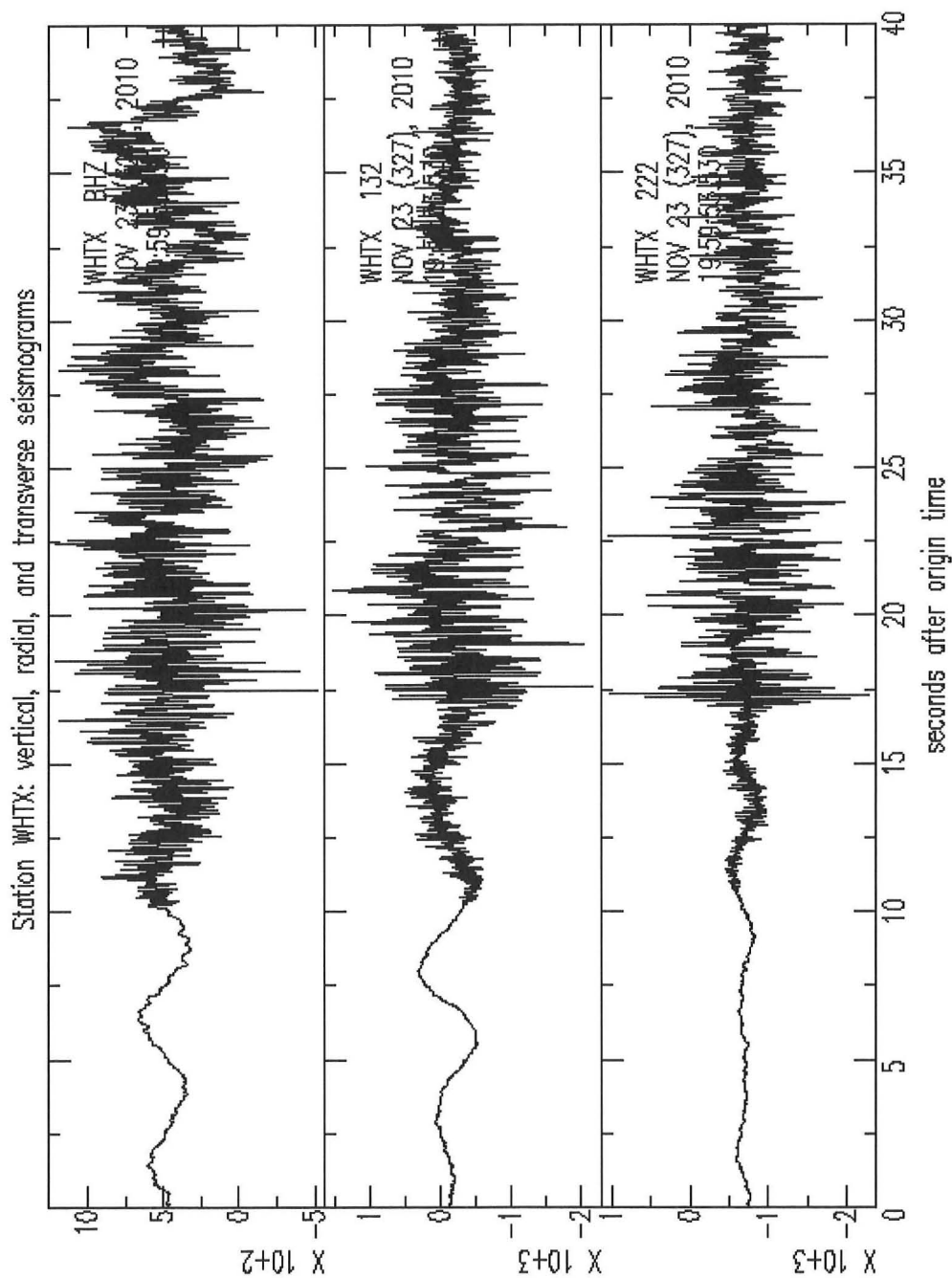


Figure 11. Seismograms at station WHTX for the earthquake of 2010 Nov 23 at 1959 near the CPNPP. The top panel is the Z-component; horizontal components are rotated to show radial (middle panel) and tangential (bottom panel) components.

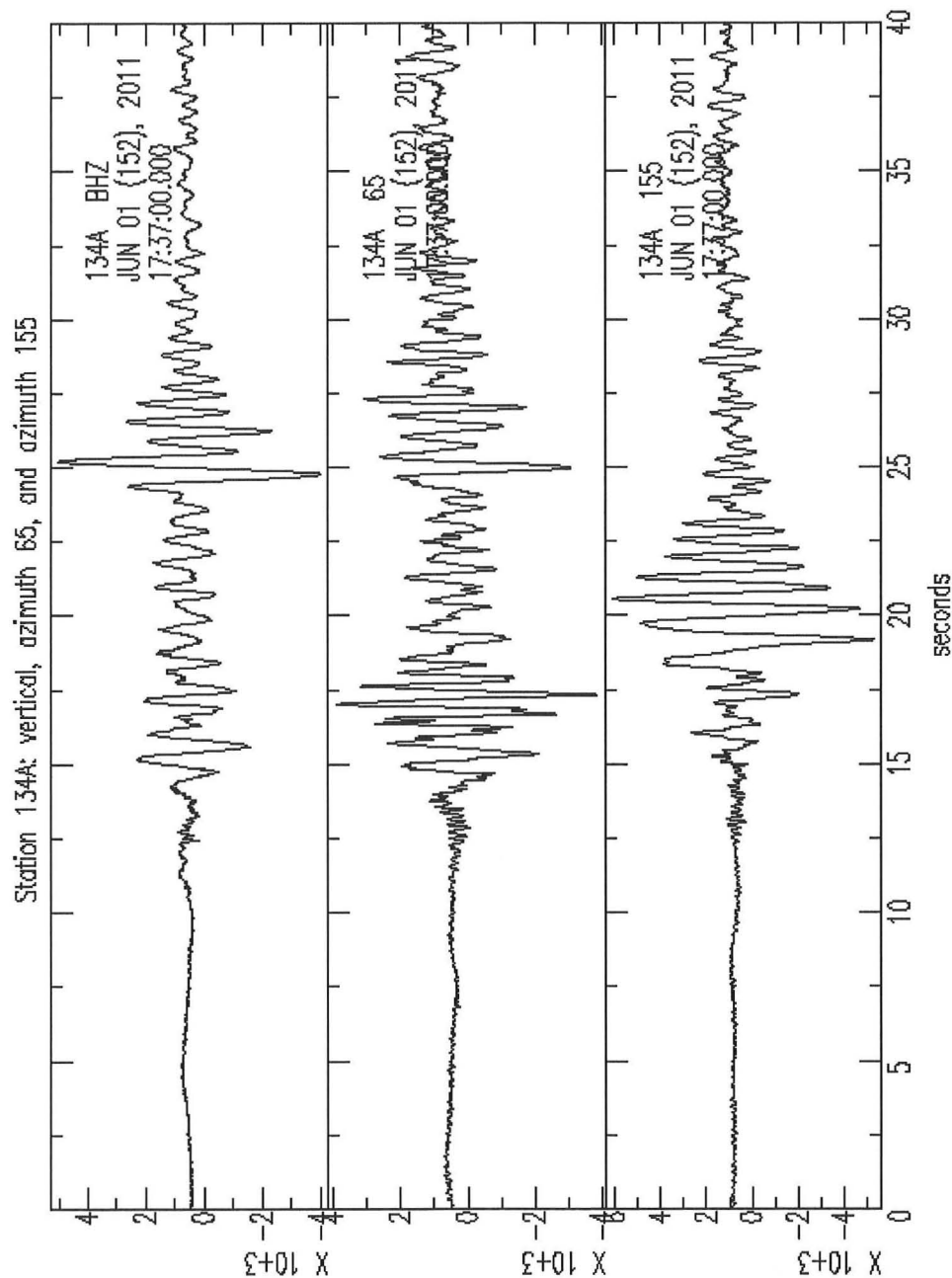


Figure 12. Seismograms at station 134A for the event of 1 June 2011 at 1737, a probable quarry blast. The top panel is the Z-component; horizontal components are rotated to azimuths of 65°E of N (middle panel) and 155°E of N (bottom panel). Particle-motion analysis for the Rg signal arriving 14-17 sec shows the motion is prograde; for the Rg signal arriving 24-28 sec the motion is regrograde. These observations suggest the source occurred in a very shallow and very low-velocity sedimentary layer.

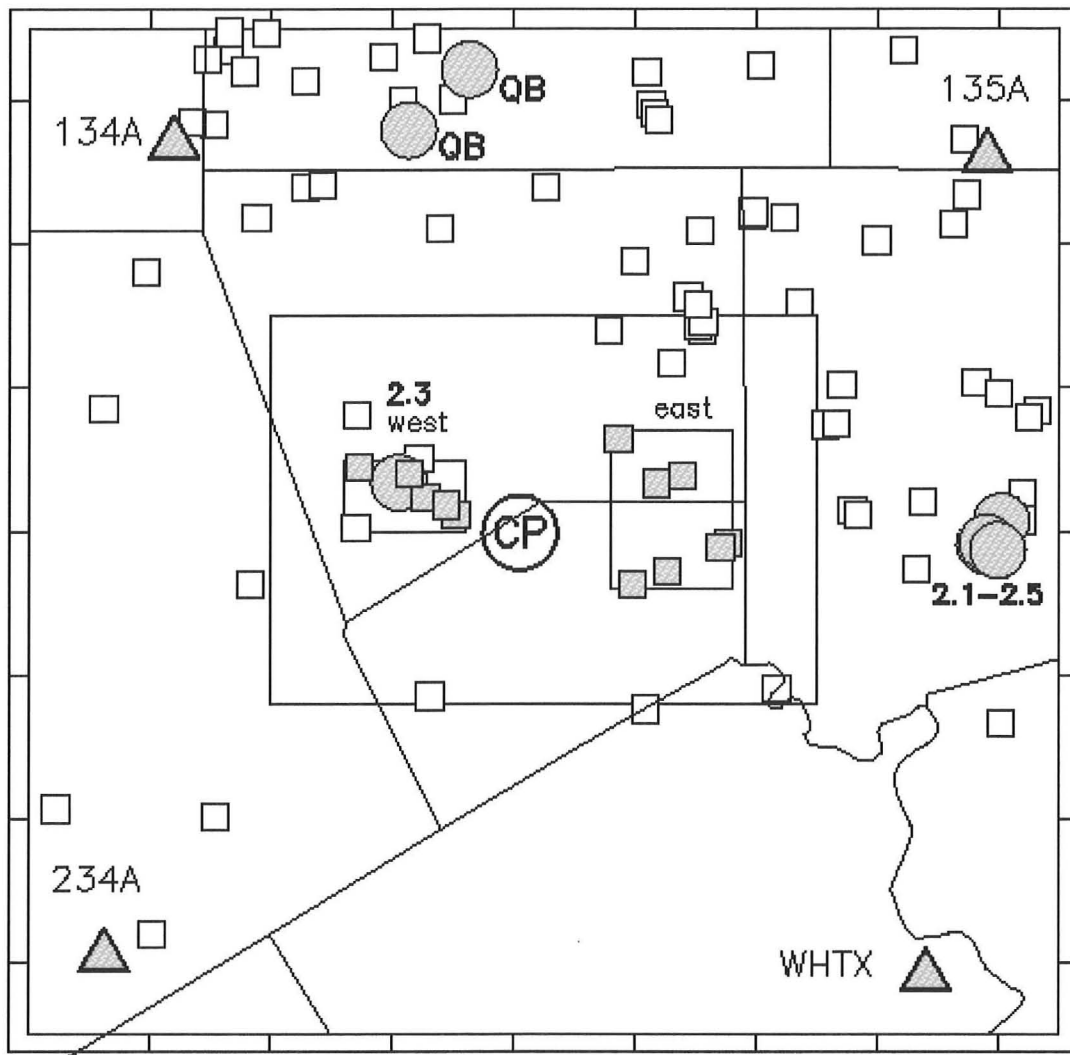


Figure 13. Map showing relationship of CPNPP (labeled circle) to seismic events determined in this study (filled circles) and to injection wells (squares) reported as active by the Texas Railroad Commission. Lines indicate county lines, the area detailed in Figure 14, and rectangular areas for wells described in the text as 'west group' and 'east group'. Filled squares indicate injection wells for which Figures 15-17 show monthly injection volumes. Numbers next to seismic events are magnitudes (see Table 5); events marked 'QB' are quarry blasts (see text and Tables 5 and 6)

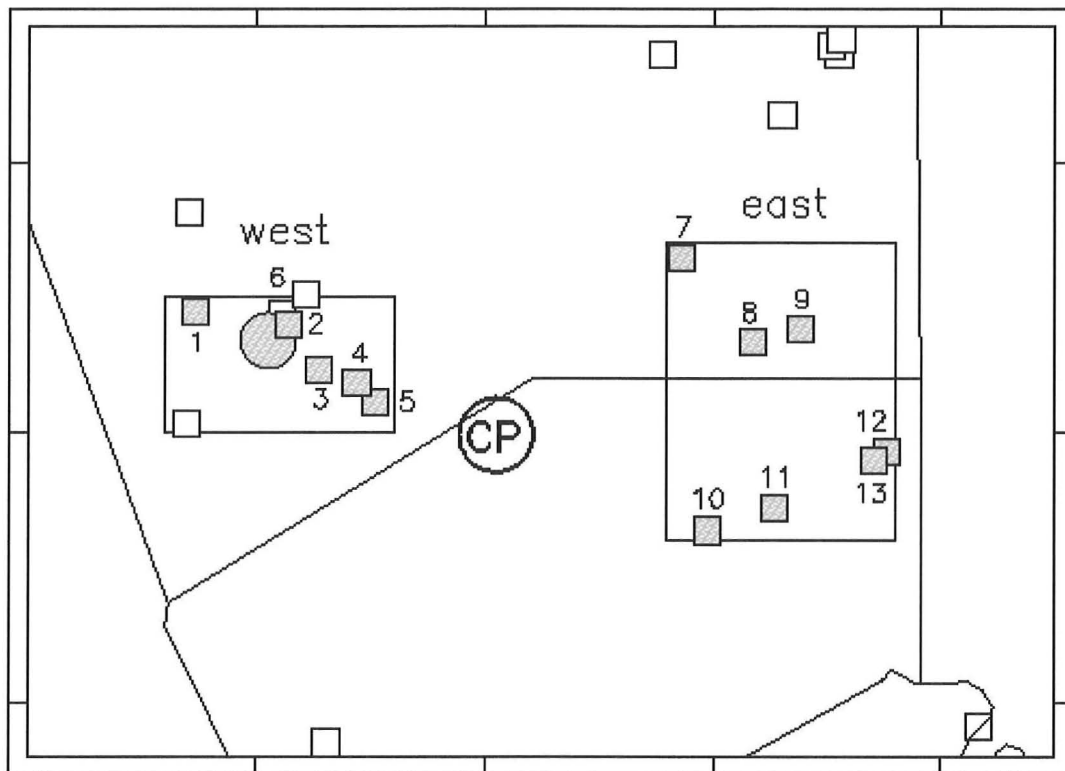


Figure 14. Detail map of Figure 13 (symbols, etc., are as in Figure 13). The numbers are the well numbers for wells with monthly injection volumes shown in Figures 15-17.

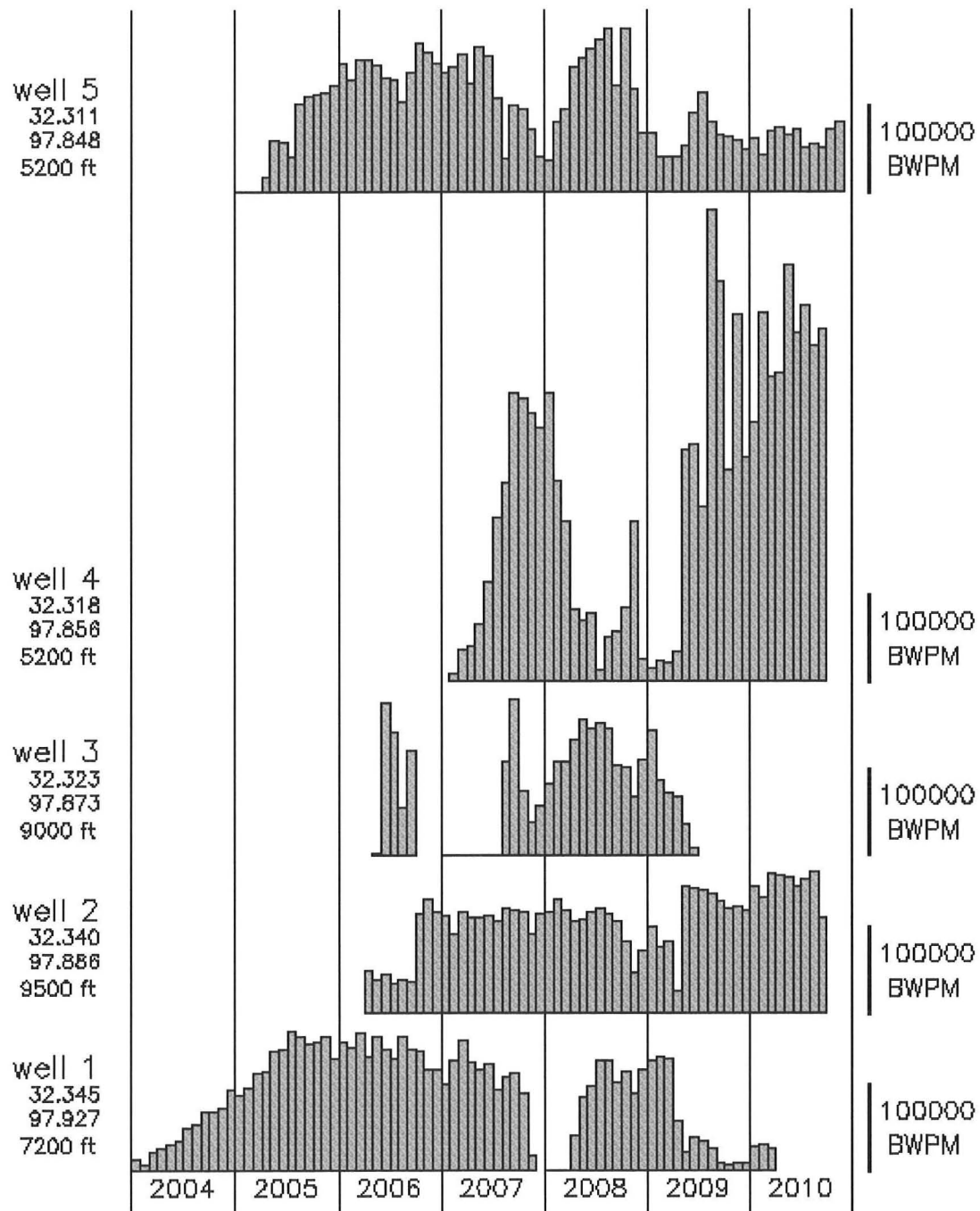


Figure 15. Monthly injection volumes reported to the Texas Railroad Commission for the wells 1-5 in the west group of injection wells in Figure 14. [No injection was reported for well 6 in the 2004-2011 period.] Well depths and locations are indicated at left; the scale bars at right indicate injection volumes of 100,000 barrels.

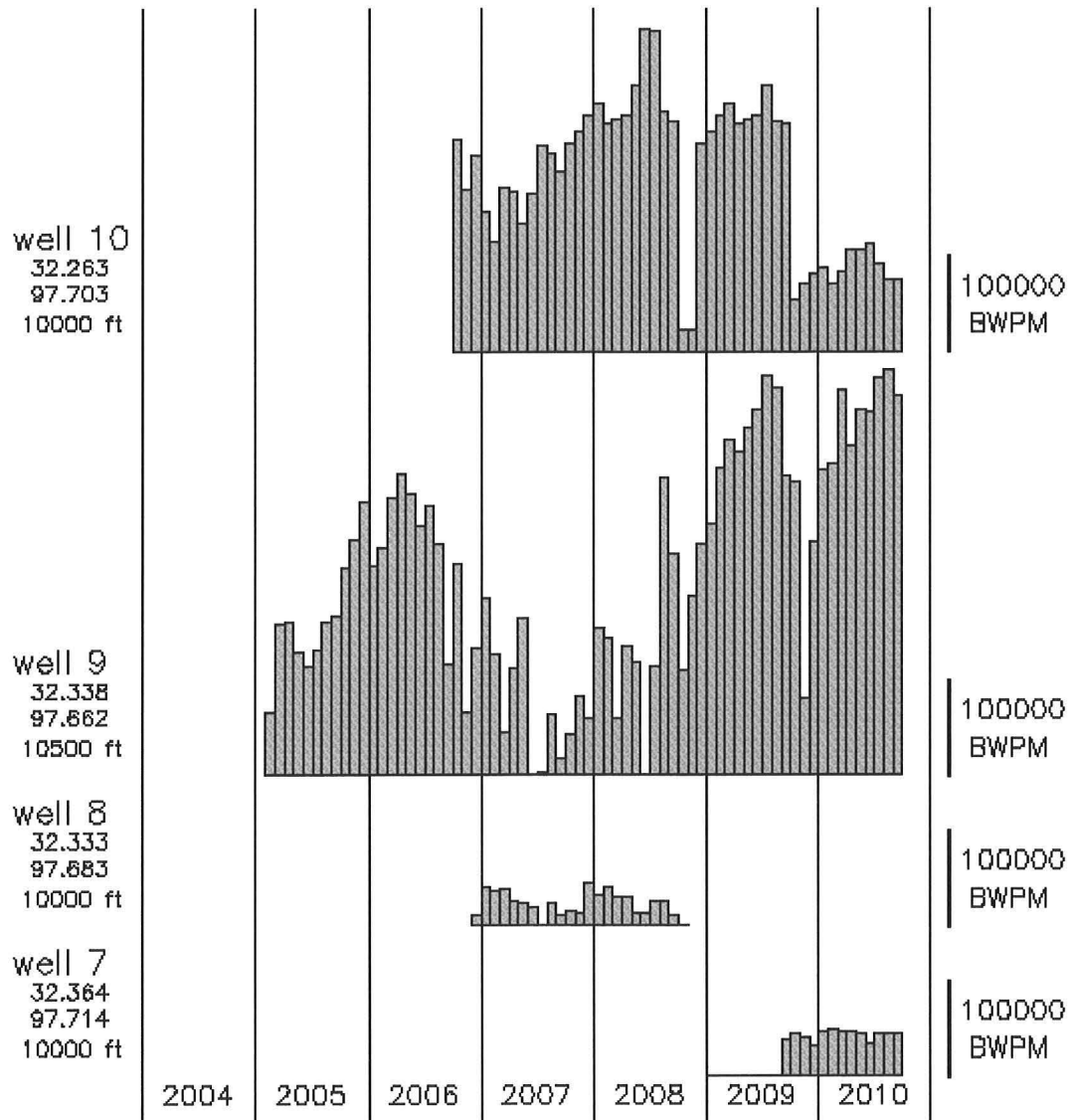


Figure 16. Monthly injection volumes reported to the Texas Railroad Commission for wells 7-10 in the east group of injection wells in Figure 14. Well depths and locations are indicated at left; the scale bars at right indicate injection volumes of 100,000 barrels.

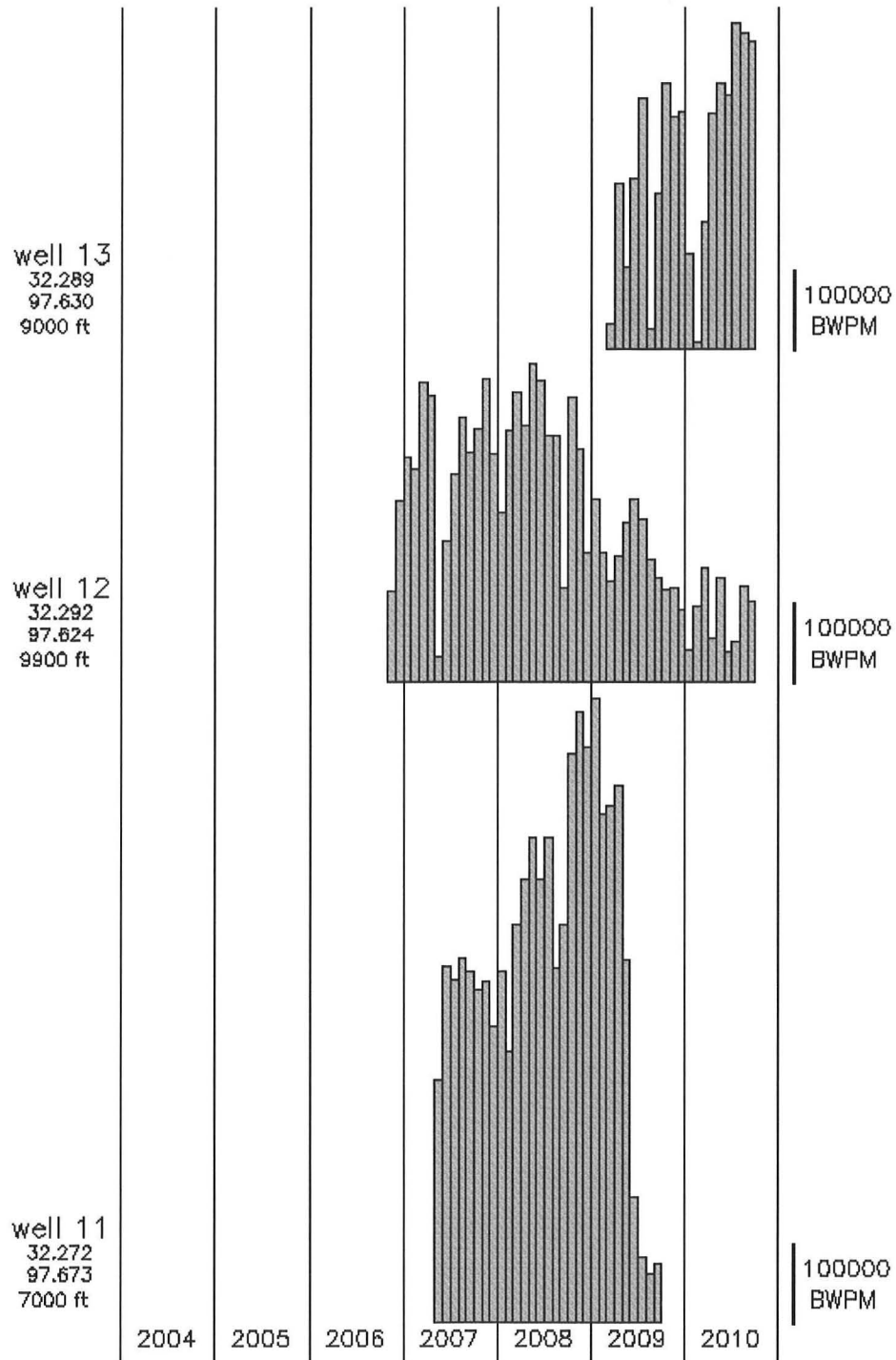
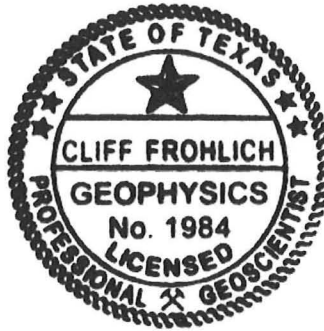


Figure 17. Monthly injection volumes reported to the Texas Railroad Commission for wells 11-13 in the east group of injection wells in Figure 14. Well depths and locations are indicated at left; the scale bars at right indicate injection volumes of 100,000 barrels.

Categories of Induced Earthquakes and Implications for Hazard at the Comanche Peak Nuclear Power Plant

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Abstract: This report reviews recent literature concerning earthquakes induced by fluid injection, focusing particularly on recent activity, and on implications for potential hazard at the Comanche Peak Nuclear Power Plant (CPNPP). We can categorize earthquakes induced by fluid injection by considering the nature and purpose of the injection (single-well injection for waste disposal, multiple-well injection for geothermal, multi-well injection for secondary petroleum recovery) and also the magnitude level of regional historical seismicity near injection well locations. Analysis of a compilation of well-documented injection-induced earthquakes indicates that with one exception, events with magnitudes exceeding M4.0 all occur in environments where natural earthquakes with larger magnitudes occur within 100 km of the well. The only exception (Snyder, TX; M4.6 1978) was in a field undergoing decades-long waterflooding at more than 100 wells spaced on a ½-km grid. The compilation found no examples where induced earthquakes having magnitudes exceeding M3.5 occurred near injection wells used for waste disposal in environments where the largest nearby natural earthquakes had magnitudes of 3.5 or less. Although 10-15 injection wells occur within 15 km of the CPNPP, this analysis suggests that if these were to induce earthquakes, their magnitudes would be smaller than M3.5.

I. Introduction

This report reviews recent developments concerning earthquakes induced by human activities, especially earthquakes apparently caused by fluid injection, as these have possible implications at the Comanche Peak Nuclear Power Plant (CPNPP). In the Fort Worth Basin horizontal drilling technology and improved hydrofracturing methods ("fracking") have stimulated considerable development of natural gas resources within the Barnett Shale since about 2002 (Montgomery et al., 2005). Analysis of low-magnitude seismic activity in the Fort Worth Basin since 2008 indicates these earthquakes are not caused by drilling, fracking, or gas production; rather they generally occur near salt water disposal (SWD) wells used to dispose of frack fluids that return to the surface during gas production. There are about 10-15 active SWD injection wells within 20 km of the CPNPP (Figure 1). This report will not discuss earthquakes induced by human activities other than fluid injection, as these are reviewed elsewhere (e.g., reservoir impoundment: Gupta, 1992; 2002; mining or cavity collapse: Gibowicz, 1991; 2001; 2009; and petroleum production: Segall, 1989; see also Suckale, 2009; 2010).

In addition to reviewing recently reported incidents of induced seismicity, this review will also categorize such incidents with respect to the nature and purpose of the injection program (single-well injection for waste disposal, multiple-well injection for geothermal, multi-well injection for secondary petroleum recovery) and also the magnitude level of regional historical seismicity near well locations. This categorization is important as it supports the assertion that induced earthquakes near the CPNPP are unlikely to have magnitudes exceeding about 3.5.

Section II of this report will describe recent reports of injection-induced earthquakes, focusing especially on those occurring since the study of Rathje and Olson (2007). Section III will present a compilation of recent examples of induced seismicity as well as examples where the induced earthquakes had magnitudes of 4.0 or greater, categorized as described above. Section IV will discuss implications for hazard at the CPNPP.

II. Recently Occurring Injection-Induced Earthquakes

IIA. Dallas-Fort Worth, Texas

Beginning on 31 October 2008, a series of small earthquakes (largest magnitude M3.0) occurred and were widely felt in Dallas-Fort Worth (DFW). The National Earthquake Information Center's (NEIC) locations were scattered over an area 10-20 km in extent; however analysis of data collected between November 2010 and January 2011 by a temporary network deployed by scientists at Southern Methodist University (SMU) indicated all the activity originated at a depth of about 4.5 km from a SW-NE-trending linear region on the Dallas-Fort Worth airport property having a dimension of about one kilometer (Frohlich et al., 2010; 2011). This trend

of activity approximately coincides with a fault mapped by Ewing (1990). In the DFW area there was no previous historical seismicity known prior to these events.

The DFW activity was situated less than a kilometer from a 4.2 km-deep SWD well operated by Chesapeake Energy to dispose of frack fluids produced at nearby production wells. Injection volumes at the well were about 10,000 barrels/day (BWPD), and injection had begun only in September 2008, six weeks before the seismic activity commenced.

A second series of felt earthquakes occurred in May 2009 (largest magnitude M3.3). Although Chesapeake discontinued injection at the SWD well in August, 2009, by this time they had installed a seismic monitoring system. They have since reported that well into 2010, occasional small unfelt earthquakes continued along the trend of the 2008 activity (Keller, 2010; see also Frohlich, 2011).

IIB. Cleburne, Texas

In June 2009 several small locally felt earthquakes (largest magnitude M2.8) occurred near Cleburne, Texas, 65 km south of the DFW activity. This activity has continued, with felt events being occasionally reported in 2010, and at least one Cleburne earthquake in 2011 located by Frohlich (2011). Here also SMU scientists installed a temporary network; preliminary locations indicated that the Cleburne activity occurred along a N-S trending linear region with length about 2 km; preliminary focal depths were mostly between about 3-4 km (Howe et al., 2010). There was no previous historical seismicity known near Cleburne prior to these events.

There were two active injection wells within about one kilometer of the Cleburne earthquakes. At one, operated by Chesapeake Energy, injection with rates of ~10,000-20,000 BWPD had been ongoing since September 2005; injection ceased in September 2009. Injection at the other well began in August 2008 and has continued, but rates have mostly been less than 3000 BWPD.

IIC. Guy-Greenbrier, Arkansas

Between October 2010 and March 2011 about 200 earthquakes locatable by a local network occurred at depths of 3-7 km along a 15-km long SW-NE linear trend between Guy and Greenbrier, AK (Horton and Ausbrooks, 2010; 2011). Several of these had magnitudes of M3.7-M4.0; then on 27 February 2011 a M4.6 earthquake occurred.

The trend of this activity lay within about three kilometers of a 3.34 km-deep well operated by Chesapeake Energy where injection had been ongoing since August 2010. There are also several other injection wells in the area, including at least two that may have caused small induced earthquakes as early as 2009. Following the February 2011 earthquake the Arkansas Oil and Gas Commission ordered a

moratorium on injection on these wells. Subsequently Chesapeake sold its regional gas assets in Arkansas.

There is a well-established record of natural seismicity in this region. Two intense swarms of earthquakes, each including M4.6 events, occurred in 1982 and 2002 near Enola, AK, 15 km southeast of the Guy-Greenbrier activity. Maps available from the Arkansas Geological Survey indicate several faults within 10 km of the recent earthquakes, including three prominent enough to be named, the Morrilton Fault, the Enders Fault, and the Heber Springs Fault.

IID. Braxton County, West Virginia

Since April 2010, news reports indicate that a series of small earthquakes (largest M3.4) occurred near Frametown, Braxton County, West Virginia; seven of these were large enough to be located by the NEIC. Frametown is home to holding tanks that store water used in hydraulic fracturing, or fracking, operations. The West Virginia Department of Environmental Protection has permitted Chesapeake Energy to use a nearby well to dispose of the frack fluids produced by wells in the Marcellus Shale. The news reports indicate that Chesapeake has disposed of about 240,000 barrels of drilling fluid at the well since 2009.

We are unaware of any previous historical earthquakes near Frametown. However, a M3.5 natural earthquake occurred at a distance of about 100 km in 1991, and the August 2011 Mineral, VA M5.8 earthquake was about 250 km distant.

IIE. Fylde Coast, United Kingdom

News reports describe two small earthquakes (M1.5 and M2.3) occurring in April and May, 2011, occurring within 2 km of an experimental frack operation on the Fylde Coast near Blackpool, United Kingdom. Allegedly injection operations began in March, 2011; following the May 2011 earthquake, Cuadrilla Resources terminated the project, allegedly "Britain's only shale gas project". The NEIC reports several previous M3-M4 earthquakes within 100 km of this location; M5.4 and M5.0 earthquakes at distances of 130-160 km occurred in 1984 and 2002.

III. Compilation

Our compilation of reports of injection-induced (Table 1) includes recently-occurring examples described in the previous section, recently-reported examples related to geothermal projects, and all known examples where the induced earthquake had a reported magnitude of 4.0 or greater. Nicholson and Wesson (1990) and Suckale (2009) list other examples. However it is the larger-magnitude examples in Table 1 that are most relevant to concerns about hazard at the CPNPP, and it is the recently-occurring examples which have contributed most to current apprehension about hazards related to induced earthquakes.

One way to categorize injection projects concerns the occurrence and magnitude of nearby natural earthquakes (Figure 2). It is plausible that hazard from injection-induced earthquakes is greater in regions where natural earthquakes are common, especially if some natural earthquakes are also large.

Other than the M4.6 1978 Snyder, TX, earthquake, all of the induced earthquakes in Table 1 having magnitudes of 4.0 or greater occur in environments where large or larger natural earthquakes also occur within 100 km:

- Induced M5.3 - Denver Rocky Mountain Arsenal, CO: Regional natural earthquakes occur nearby and an earthquake with estimated magnitude M6.6 occurred in 1882 at about 100 km distance;
- Induced M4.7 - Guy-Greenbrian, AK: NEIC reports natural earthquakes within 20 km with M4.7 in 1982 and 2002;
- Induced M4.6 - Geysers, CA: M7 and larger earthquakes occur regularly on nearby San Andreas Fault. NEIC reports several M4.5-M5.0 earthquakes within 100 km.
- Induced M4.4 - Berlin, El Salvador: This project is near a volcano in a subduction-zone environment in a small country with a history of damaging earthquakes (e.g., M7.5 in 1986).
- Induced M4.3 - Paradise Valley, CO: Here natural earthquakes occurred within 20 km of the site prior to the initiation of injection; in 1994 an M4.6 occurred at a distance of 80 km. Several earthquakes larger than M5.0 have occurred within 100-150 km (Ake et al., 2005).
- Induced M4.0 - Permian Basin, TX: The 1992 M5.0 Rattlesnake Canyon natural earthquake occurred within the Permian Basin.

A second way to categorize injection projects concerns the number of injector wells in the project and project's objective. Most waste-disposal operations utilize a single well and usually strive to avoid injecting too close to mapped faults since wastes reaching a fault might travel upward and contaminate groundwater. Many waste-disposal wells are used only sporadically or are in operation for only a few years. In contrast, geothermal operations often utilize several wells situated a few km apart, injecting fluids into some and extracting hot water or steam from others. And secondary recovery operations may involve numerous wells on a grid spacing of a km or less, and inject enormous amounts of fluid during a several-year period when a field is being produced.

Geothermal operations usually involve multiple injecting wells and may be active for decades; however, none have yet induced an earthquake with magnitude exceeding M4.6 (Table 1; Figure 2). For example, the Geysers geothermal field in California has been in operation for about 50 years. Both examples in Table 1 where the induced earthquake had a magnitude exceeding M4.0 (Geysers, CA; and Berlin,

El Salvador) occurred near plate boundaries in environments where large natural earthquakes are common.

The 1978 induced M4.6 earthquake in Snyder, TX, occurred in the Cogdell Oil Field undergoing a massive waterflooding operation to enhance recovery (Davis and Pennington, 1989). This involved injection into more than 100 wells, spaced at half-km intervals and extending over an area with dimensions ~5 km X 20 km, lasting for decades, with volumes of several million barrels of water per month, pumped with the express intent of creating significant overpressures for extended periods over extensive regions. The M4.4 Snyder earthquake that occurred on 11 September 2011 also is likely to be caused by injection associated with secondary recovery operations, as these persist to this day.

Although the Snyder earthquakes appear to be induced by fluid injection and occurred in a region that had been previously virtually aseismic, the physical changes induced in the subsurface by these massive waterflooding operations dwarf those caused by the ordinary waste disposal operations ongoing near the site of the CPNPP. Moreover, with magnitudes of M4.6 and M4.4 and a distance of 290 km from the CPNPP site, the Snyder earthquakes pose no physical threat to the facility.

Similarly, the 20 October 2011 M4.8 earthquake that occurred southeast of San Antonio, Texas, at a distance of 390 km from the CPNPP, does not constitute a hazard. Although hydrofracturing has recently been applied to develop gas production in the Eagleford Shale, it is unlikely fracking or fluid injection was responsible for the 20 October earthquake. Natural gas has been produced in this region since the 1940's and there have been numerous earthquakes since 1973, including an M4.3 on 9 April 1993 (Davis et al. 1995). All these earthquakes have had epicenters within or at the boundaries of natural gas fields being produced by conventional methods (not fracking). The literature suggests these earthquakes occur along the same faults that provide the traps for natural gas, and are caused by fluid withdrawal, i.e., differential compaction induced by depressurization of the field (Pennington et al., 1986). There are no similar geological formations or conventional gas fields of this type in the vicinity of the CPNPP. Thus the occurrence of the 20 October earthquake isn't directly relevant to the discussion in this report

In contrast, the three examples in Table 1 most similar to the situation at the CPNPP all occurred near single-well injectors in a tectonic environment where regional seismicity is absent or of small magnitude:

- Induced M3.3 - Dallas-Fort Worth, TX: largest natural earthquake within 100-130 km have M3.3 or 3.4;
- Induced M2.8 – Cleburne, TX: largest nearby natural earthquake is M3.4 at 140 km distance;
- Induced M3.4 – Braxton County, WV: largest natural earthquake within 100 km is M3.5.

IV. Discussion – Implications for Hazard at the CPNPP

It is worth noting that Texas has more injection wells than any other state and Texas well operators have been injecting for the purposes of secondary recovery and waste disposal since the 1930's. According to Doug Johnson, Manager for Injection and Storage Permits at the Texas Railroad Commission, there are more than 100,000 injection wells in Texas. This includes 39,000 wells permitted for stimulation (e.g., secondary recovery) of which 25,000 are active, and 12,000 wells permitted for waste disposal, with 5000 are presently active (Doug Johnson, personal communication). Thus from one perspective, Texas has been a vast natural laboratory experimenting on whether injection induces earthquakes large enough to be felt by humans. The experiment so far indicates that injection induces noticeable earthquakes only rarely (e.g., Davis and Pennington, 1989; Doser et al., 1992; Frohlich et al., 2010; 2011; Howe et al., 2010; Frohlich, 2011) and none have caused significant damage.

Why induced earthquakes occur in some environments and not others is still poorly understood. Earthquake researchers only established that fluid injection could induce earthquakes in the 1960's. For obvious reasons, much of the published research describes analysis of post-earthquake data following those exceptional events large enough to be noticed by the public. With a few exceptions (e.g. Paradise Valley, CO; Ake et al., 2005), most of the literature describes situations where local monitoring networks were only set up after the earthquake occurred. The literature available at present simply hasn't addressed the question of how large a yet-to-occur induced earthquake might be.

Nevertheless, three relevant trends are evident in this report's compilations (Table 1; Figure 2):

- The largest injection-induced earthquake from any cause in any tectonic environment had magnitude M5.3 (Denver, CO, 1967).
- With the exception of M<3 induced earthquakes in environments where no natural nearby seismicity occurs, all but one of the injection-induced earthquakes are no larger than the largest natural earthquake occurring within 100 km. The remaining exception (1978 Snyder, TX, M4.6) was caused by a massive waterflooding project involving more than 100 injection wells, a situation highly unlike the injection near the CPNPP.
- In the environment most similar to that near the CPNPP—where no natural earthquakes have M>3.5 and where injection is to dispose of wastes—the largest induced earthquakes have M<3.5.

Earthquakes are only likely to pose a hazard to the CPNPP if they occur nearby and relatively large. Although there are active injection wells within 15 km of the CPNPP, the compilations (Table 1 and Figure 2) suggest that any earthquakes they induce probably will have magnitudes smaller than M3.5.

Finally, it is important to reiterate that there is no evidence that 'fracking' causes earthquakes large enough to pose a hazard to the CPNPP. Because fracking fractures rock the seismic signals produced are, in a strict sense, earthquakes, but there is no evidence that the induced earthquakes of concern for hazard analysis are 'frack jobs that got out of hand'. Rather, the seismic signals generated by fracking typically have magnitudes of -3.5 to 1.0. The induced earthquakes of interest in this report are not caused by fracking, but rather when frack fluids that return to the surface undergo disposal into deep strata using injection wells.

References

- Ake, J., K. Mahrer, D. O'Connell and L. Block (2005). Deep-injection and closely monitored induced seismicity at Paradox Valley, Colorado, *Bull. Seismol. Soc. Amer.*, 95, 664-683, doi:10.1785/0120040072.
- Davis, S. D., P. A. Nyffenegger and C. Frohlich (1995). The 9 April 1993 earthquake in south-central Texas: Was it induced by fluid withdrawal? *Bull. Seismol. Soc. Amer.*, 85, 1888-1895, 1995.
- Davis, S. D. and W. D. Pennington (1989). Induced seismic deformation in the Cogdell oil field of West Texas, *Bull. Seismol. Soc. Amer.*, 79, 1477-1495.
- Doser, D. I., M. R. Baker, M. Luo, P. Marroquin, L. Ballesteros, J. Kingwell, H. L. Diaz and G. Kalp (1992). The not so simple relationship between seismicity and oil production in the Permian Basin, West Texas, *Pure Appl. Geophys.*, 139, 481-506.
- Ewing, T. (1990). *Tectonic Map of Texas*, published by Univ. Texas Bureau of Economic Geology.
- Frohlich, C. (2011). *Search for Small (M2-M3) Earthquakes near the Comanche Peak Nuclear Power Plant Using 18 Months of Data Recorded at Four Nearby Temporary Seismograph Stations*, FUGRO Consultants Tech. Report.
- Frohlich, C., E. Potter, C. Hayward and B. Stump (2010). Dallas-Fort Worth earthquakes coincident with activity associated with natural gas production, *Leading Edge*, 29, 270-275, doi:10.1190/1.3353720.
- Frohlich, C., C. Hayward, B. Stump and E. Potter (2011). The Dallas-Fort Worth earthquake sequence: October 2008 through May 2009, *Bull. Seismol. Soc. Amer.*, 101, doi:10.1785/0120100131
- Gibowicz, S. J. (1991). Seismicity induced by mining, *Advances Geophys.*, 32, 1-74.
- Gibowicz, S. J. (2001). Seismicity induced by mining: Ten years later, *Advances Geophys.*, 44, 39-181.
- Gibowicz, S. J. (2009). Seismicity induced by mining: Recent research, *Advances Geophys.*, 51, 1-53.

- Gupta, H. K. (1992). *Reservoir-Induced Earthquakes*, Elsevier.
- Gupta, H. K. (2002). A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India, *Earth Sci. Rev.*, 58, 279-310.
- Horton, S. and S. M. Ausbrooks (2010). Are recent earthquakes near Greenbrier, Arkansas, induced by waste-water injection? *Seismol. Res. Letts.*, 81, 378.
- Horton, S. and S. M. Ausbrooks (2011). Possible induced earthquakes in central Arkansas, *Seismol. Res. Lett.*, 82, 279.
- Howe, A. M., C. T. Hayward, B. W. Stump, and C. Frohlich (2010). Analysis of recent earthquakes in Cleburne, Texas, *Seismol. Res. Lett.*, 81, 379.
- Hsieh, P. A. and J. S. Bredehoeft (1981). A reservoir analysis of the Denver earthquakes—A case study of induced seismicity, *J. Geophys. Res.*, 86, 903-920.
- Keller, W. K. (2010). Operator evaluation of the impact of fluid injection into shale reservoirs, *Abstracts: AAPG/SEG/SPE/SPWLA Hedberg Conference, Critical Assessment of Shale Resource Plays*, Dec. 5-10, 2010, Austin, TX.
- Majer, E. L., R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith and H. Asanuma (2007). Induced seismicity associated with Enhanced Geothermal Systems, *Geothermics*, 36, 185-222, doi:10.1016/j.geothermics.2007.03.003.\
- Montgomery, S. L., D. M. Jarvie, K. A. Bowker and R. M. Pollastro (2005). Mississippian Barnett shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential, *AAPG Bull.*, 89, 155-175, doi:10.1306/09170404042.
- Nicholson, C. and R. L. Wesson (1990). Earthquake hazard associated with deep well injection: A report to the U.S. Environmental Protection Agency, *U.S. Geol. Surv. Bull.* 1951, 74 pp.
- Pennington, W. D., S. D. Davis, S. M. Carlson, J. DuPree and T. E. Ewing (1986). The evolution of seismic barriers and asperities caused by the depressuring of fault planes in oil and gas fields of south Texas, *Bull. Seismol. Soc. Amer.*, 76, 939-948.
- Rathje, E. M. and J. E. Olson (2007). *Technical Issues Related to Hydraulic Fracturing and Fluid Extraction/Injection near the Comanche Peak Nuclear Facility in Texas*, William Lettis & Associates, Inc., Technical Report, WLA Project No. 1908.
- Suckale, J. (2009). Induced seismicity in hydrocarbon fields, *Advances Geophys.*, 51, 55-106, doi:10.1016/S0065-2687(09)05107-3.

Table 1. Recent and higher-magnitude reports of injection-induced seismicity. The table strives to be inclusive for locations reported since 2007 and for locations where largest-magnitude induced earthquake was M4.0 or greater. Nicholson and Wesson (1990), Suckale (2009) and Figure 2 (this report) show additional locations where largest-magnitude induced earthquakes were smaller than M4.0. Table is arranged in order of increasing size of reportedly induced earthquakes.

<i>location and reference</i>	<i>category</i>	<i>injection properties duration, depth</i>	<i>earthquakes</i>	<i>regional natural earthquakes properties</i>	<i>notes</i>
Injection wells near 23 Nov 2010 CPNPP quake (Frohlich, 2011) Fylde Coast, Great Britain (news reports; NEIC)	single-well injection; waste disposal; several wells within 5 km area single-well injection; waste disposal	2004-present: wells 1.6-2.9 km depth began Mar 2011	one only: M2.3 Nov 2011 M2.3 in April 2011, 2 km from well	NEIC reports no natural quakes within 100 km of wells NEIC reports several M3-M4 quakes within 100 km; 1984 M5.4 and 2002 M5.0 quakes at 130-160 km	"Britain's only shale-gas project"
Cleburne, TX (Howe et al., 2010)	single-well injection; waste disposal	Sep 2005; some injection ongoing	Quakes first felt June 2009, largest M2.8 within 2 km of well	local natural earthquakes rare or unknown	1997 M3.4 Commerce TX quake at 140 km distance
Soultz-sous-Forets, France (Majer et al., 2007)	multi-well injection; ~9 wells; geothermal	late 1990's; depth 5 km	largest M2.9, June 2003	NEIC reports seven >M4.5 quakes within 120 km, including M5.9 in 1978	
Dallas-Fort Worth, TX (Frohlich et al., 2010; 2011)	single-well injection; waste disposal	Sep 2008- Aug 2009; 4.2 km well	quakes began Oct 2008; largest M3.3, within 1 km of well; continue into 2010 after injection stops	local natural earthquakes rare or unknown	NEIC reports 1985 M3.3 quake at 75 km distance; M4.0-4.5 OK quakes at 200-250 km distance
Braxton County, West Virginia (news reports; NEIC)	single-well injection; waste disposal	began Spring 2009	M3.4 in April 2010	largest NEIC-reported earthquake within 100 km was M3.5 in 1991	~250 km from M5.8 August 2011 Mineral, VA quake
Basel, Switzerland (Majer et al., 2007)	single-well injection?; geothermal	began 2 Dec 2006; depth 5 km	largest M3.4, 8 Dec 2006; near injection well	NEIC reports 2004 M4.8 within 100 km; numerous quakes with M>4	M6.5 damaged Basel in 1356; 2006 quake shut down geothermal project

<i>location and reference</i>	<i>category</i>	<i>injection properties duration, depth</i>	<i>earthquakes</i>	<i>regional natural earthquakes properties</i>	<i>notes</i>
Cooper Basin, Australia (Majer et al., 2007)	single-well injection; geothermal	began 2003; 4.4 km depth	largest M3.7 Dec 2003; most seismicity within 1 km of well	NEIC reports M3.6 at ~50 km distance in 1989	
Permian Basin, TX and NM (Doser et al., 1992; Nicholson and Wesson, 1990)	secondary recovery; multi-well; many different fields	began 1959 and subsequently; depths 0.74-3.66 km	largest ~M4.0	largest natural quake in Permian Basin is M5.0 1992 Rattlesnake Canyon event	
Paradise Valley, western CO (Ake et al., 2005)	single-well injection; waste disposal	1996 – 2005...; 4.3-4.8 km well	thousands of quakes recorded by local network; largest M4.3 May 2000 about 3 km from injector	natural quakes within 20 km of well recorded by local network prior to injection; 1994 M4.6 at 80 km distance	four quakes with M>5 have occurred since 1970 within 150-300 km of well
Berlin, El Salvador (Majer et al., 2007)	multi-well injection; geothermal	1990's – present?; 8 wells 2003	M4.4 2003, 3 km from injection well	high-seismicity region; M7.7 2001 El Salvador earthquake	volcano nearby
Snyder, TX, Cogdell field (Davis and Pennington, 1989)	secondary recovery; injection at more than 100 wells on half-km spacing	began 1956- active to 1983; depth 2.1 km	largest M4.6 1978; quakes 1974-1982	local natural earthquakes rare or unknown	Nearest M5 natural quakes are 1992 Rattlesnake Canyon, and 1925, 1936 in Texas Panhandle
Geysers, CA (Majer et al., 2007)	multi-well injection; geothermal	~1960 –present; injection now at 9 wells separated by only a few km; Aug 2010 – Mar 2011; depth 3.5 km at well #5.	largest M4.6 1982; 2 or 3 M4.0 or greater each decade	NEIC reports several M4.5-M5.0 within 100 km of field	about 150 km from San Francisco; closer to San Andreas Fault
Guy-Greenbriar, AK (Horton and Ausbrooks, 2010; 2011)	single-well injection; waste disposal; several wells in 10-km area	Mar 1962- Feb 1966; 3.67 km well	largest M4.7 Feb 2011; numerous smaller events	natural quakes within 20 km of well recorded by local network prior to injection	NEIC reports natural M4.7 quakes in 1982 and 2001 within 25 km of well
Denver, Rocky Mountain Arsenal, CO (Hsieh and Bredehoeft, 1981)	single-well injection; waste disposal	Mar 1962- Feb 1966; 3.67 km well	quakes began Apr 1962; several with M~5; largest M5.3 Aug 1967, several km from injector	natural M6.6 in Nov 1882 about 100 km N of Denver	quakes with M>5 have occurred since 1970 about 300 km from Denver to S, W, and N

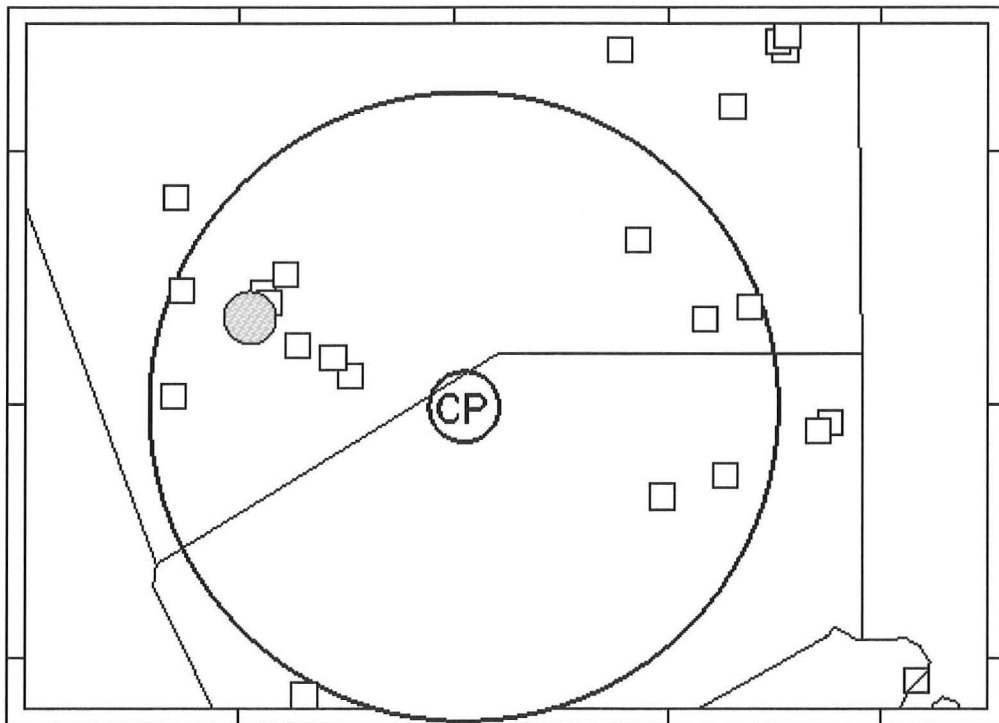


Figure 1. Map of the region surrounding the Comanche Peak Nuclear Power Plant (CPNPP), showing injection disposal wells (squares) as reported by the Texas Railroad Commission, and a 23 November 2010 M2.3 earthquake (filled circle) located by Frohlich (2011). The circle labeled 'CP' is centered on the CPNPP and has a radius of 15 km.

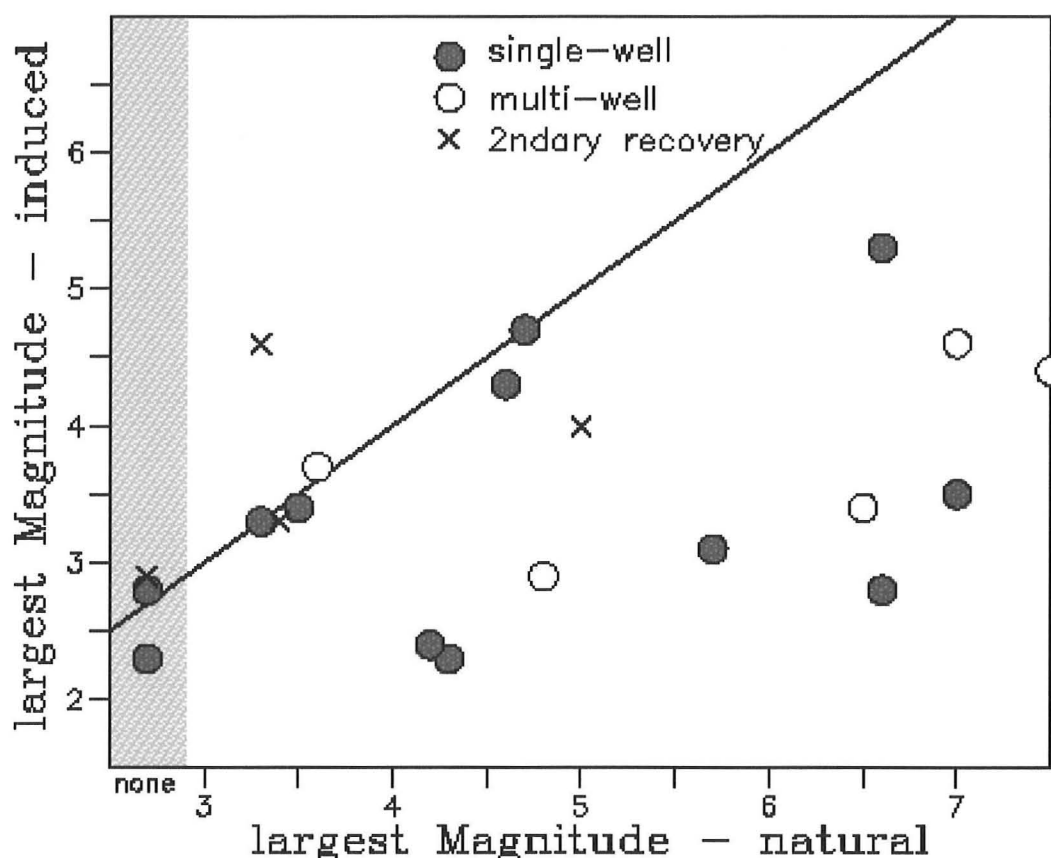


Figure 2. Comparison of largest magnitudes for induced earthquakes and natural earthquakes occurring within 100 km of injection site. Magnitudes for induced earthquakes are as reported in the literature; magnitudes for natural earthquakes are as reported by NEIC or, when known large events have occurred prior to 1973, from historical sources. Figure includes all examples in Table 1, all induced examples categorized as caused by injection reported by Suckale (2009), and all that Nicholson and Wesson (1990) categorized as caused by injection, excluding those categorized only as 'less well documented or possible'. Symbols indicate examples where injection was at a single well (usually for waste disposal), at multiple wells (usually for geothermal projects), and for secondary recovery (always involving numerous wells). Examples plotted on grey bar at left are induced earthquakes where no historical earthquakes within 100 km were found.