ABSTRACT

RE-EVALUATION OF THE 2009-2011 SOUTHERN FORT-WORTH BASIN (TX) EARTHQUAKES: POTENTIAL RELATIONSHIPS WITH HYDRAULIC FRACTURING AND WASTEWATER INJECTION

by Sarah Liora Rigelhaupt Smith

North Texas has seen an increase in seismic activity around the Dallas/Fort Worth area since the early 2000’s, with activity in Johnson County in particular culminating in magnitude 3 and 4 events in 2011 and 2015 respectively. Previous analysis of the Johnson County sequence between 2009 and 2011 concluded that many of the events were induced by wastewater injection (Frohlich, 2012), however the earthquake database was small during this time period, and the differences between inducing and non-inducing injection wells were not clearly identified. This study addresses the causes of recent seismicity in Johnson County through an in depth characterization of the seismicity, industry operations, and regional and local geology in North Texas from 2009 to 2011. Seismic template matching using 3 USArray Transportable Array station recordings of all previously cataloged earthquakes in the study area provide a more complete temporal history of seismicity, identifying 977 additional events. Earthquakes from the largest burst in activity, in June 2011, were relocated using hypoDD and seem to align along NNE-SSW trends consistent with regional stress orientations and pre-existing structures related to the adjacent Ouachita thrust front. Relocated seismicity outlines a fault plane in the Precambrian basement that extends approximately 4 km in vertical extent, and is consistent with the hypothesis that seismicity is occurring on reactivated, pre-existing, critically stressed faults. Monthly injected volumes from 9 wastewater disposal wells suggest a correlation with background levels of seismicity throughout the study timeframe, however they do not correlate with distinct spikes in seismic activity. Temporal patterns of seismicity during the June 2011 sequence resemble patterns seen in previously documented cases of hydraulically fractured induced seismicity in Ohio. While a complete stimulation database is not available from this time frame, the vast number of active hydraulic fracturing wells in the region as identified from production data indicate that the possibility that this sequence is spatially and temporally correlated with hydraulic fracturing wells cannot be dismissed.
RE-EVALUATION OF THE 2009-2011 SOUTHERN FORT-WORTH BASIN (TX) EARTHQUAKES: POTENTIAL RELATIONSHIPS WITH HYDRAULIC FRACTURING AND WASTEWATER INJECTION

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1. Introduction

Since the early 2000s, an increase in earthquakes induced oil and gas industry operations in the central continental US has brought the issue to the forefront of seismology. More than 180 M>3 earthquakes occurred in 2011, compared with an average of 21 earthquakes/year between 1967 and 2000 (Ellsworth, 2013), and rate is higher yet today. Many earthquakes in Oklahoma, Texas, Ohio, Colorado, and Arkansas, have been associated with both wastewater injection (e.g. Horton, 2012; Keranen et al., 2013; Yeck et al., 2015; Weingarten et al., 2015) and hydraulic fracturing (e.g. Holland, 2013; Skoumal et al., 2015a, 2015b). While induced seismicity associated with oil and gas operations in the US has been well documented since the 1960s (Healy et al., 1968; Raleigh et al., 1976), the rate of increase in recent years has prompted further research and seismic hazard reassessments for this region of the US (Petersen et al., 2015). Understanding the mechanics and causes of induced seismicity are necessary for developing practices and policies that will help mitigate future hazards.

The Fort-Worth Basin (FWB) in Texas, is an area that has experienced a dramatic increase in observed seismicity. While prior to 2008 the basin experienced little to no seismicity, numerous earthquake sequences have since been reported including a 2008-2009 sequence near the Dallas-Fort Worth International airport (Frohlich et al., 2011), in Cleburne from 2009-2010 (Justinic et al., 2013) and in Azle in 2013 (Hornbach et al., 2015). These events, as well as additional smaller events across the basin have all been attributed to either wastewater injection or secondary-recovery operations (Hornbach et al., 2016).

While most of the events in the FWB seismic sequences have been of magnitudes ≤~3.0, a M 4.0 event was associated with a sequence that occurred near Venus in 2015. Previous work on the Venus earthquake sequence (Frohlich, 2012; Frohlich et al., 2016), concluded that an increase in seismicity was due to wastewater injection as earthquakes were spatially correlated with high volume injection wells, and there was an overall increase in injected volumes in the basin over the studied time frames. Since 2015, additional seismic networks have been deployed to gain a better resolution of seismicity (such as TexNet and NetQuakes); however the lack of available local stations at the onset of seismicity in late 2008 has made it difficult to gain a full catalog with high resolution locations and a low magnitude of completeness. The USArray Transportable Array (TA) rolled through the FWB from late 2008-late 2011 and was utilized by Frohlich in his 2012 study, yet the closest station was still ~20 km away from the main
earthquake epicenters. Precise earthquake locations are imperative for studies of induced seismicity, as induced events are traditionally characterized by their spatial and temporal correlation with the wells in question (Davis & Frohlich, 1993). While the Frohlich (2012) study provided a more complete catalog of seismicity between 2009 and 2011 than was previously available, it is difficult to correlate seismicity over the course of two years with individual wells based on a catalog of 32 events. Additionally, while many high volume injectors linked to induced events were located close to the recorded seismicity, numerous wells in the basin with similar injected volumes produced no seismicity. To date, no studies have investigated potential design or operational characteristics for the injection wells linked to induced events.

The study presented below was conducted to more fully characterize the seismicity that occurred in northeast Johnson County between 2009-2011 using waveform matching techniques utilized in induced seismicity cases in other parts of the US. The overall goal of the investigation is to generate a more complete catalog of the local seismicity during this time period, provide details on the timing and location of recorded events, and identify possible links between industry operations and recorded events.

1.1 Geologic Background and Stratigraphy

The FWB is a NE dipping Paleozoic foreland basin formed during the Ouachita Orogeny as a part of the convergence of Laurussia with Gondwana (Figure 1a). It is bound by a few structural features, including the Ouachita thrust front to the east, the Muenster and Red River arches to the north, the Llano Uplift to the south, and the Concho Platform-Bend Arch to the west (Montgomery et al., 2005; Pollastro et al., 2007). The Ouachita thrust front marks the leading edge of the Ouachita orogenic belt, which extends 2,000 km through Texas, Oklahoma, and Arkansas. The Ouachita thrust front defines the eastern edge of the FWB, and lies in the subsurface near the border of Johnson and Ellis counties, ~10 km from Venus seismicity. The basement uplifts and reverse faulting of the Muenster and Red River arches to the North, mark the eastern continuation of the Amarillo-Wichita uplift, formed from reactivation of basement faults associated with Late Proterozoic development of the Oklahoma aulocogen (Walper, 1977; 1982). The Llano uplift, the southern basin boundary, is a structural dome of exposed Precambrian and Paleozoic rocks that extends northward into the Bend Arch, a N-S trending ridge formed in Late Mississippian to Early Pennsylvanian that represents a flexural bulge and
western edge of the basin (Johnson, 1988). Also notable is the Mineral Wells-Newark East fault system north of Dallas Fort-Worth, which is comprised of a series of NE-SW striking faults, and an area that has had active gas production reaching back to the 1980s.

Current hydrocarbon production in the FWB is focused in the Mississippian Barnett Shale. While the Barnett Shale has been known for decades to be a prolific hydrocarbon source rock, current production has been made economic through the utilization of horizontal drilling and multi-stage hydraulic fracturing completions. The recent rise in hydraulic fracturing across the basin has increased not only hydrocarbon production, but has also generated significant volumes of wastewater in the form of flowback and produced water. The Ordovician Ellenburger Group, a highly paleokarsted and fractured limestone sitting unconformably below the Barnett and above the older Cambrian strata (e.g. the Wilburn, Riley and Hickory formations), serves as the major wastewater disposal formation. Upper Paleozoic carbonates and clastics overly the Barnett Shale, and a thin cover of Cretaceous fill is present in the eastern part of the basin. At its deepest, the FWB has >3.7 km of sedimentary fill in the NE corner by the Muenster Arch (Montgomery et al., 2005; Pollastro et al., 2007).

Within Johnson County, the basement cover contact lies between approximately 3.4-4.2 km depth based on structure contour and isopach maps of the Ellenburger Group (Texas Water Development Board, 1972). In this part of the basin, the Ordovician Viola limestone and Simpson Group are absent, with Mississippian rocks resting directly above the Ellenburger Group. Between November 2009 and October 2011, there were 408 active producing wells and 9 active wastewater injection wells in NE Johnson County as defined by the coordinates in Figure 1b.

1.2. Mechanics of Induced Earthquakes

Earthquakes occur on a fault when the frictional resistance to slip is overcome by the applied shear stresses, as defined by the Mohr-Coulomb law:

\[ \tau_{\text{crit}} = \mu (\sigma_n - P) + \tau_0 \]

where the critical shear stress (\(\tau_{\text{crit}}\)) is equal to the product of the coefficient of friction (\(\mu\)) and the effective normal stress, given by the difference between the normal stress (\(\sigma_n\)) and the pore-
fluid pressure (P), and \( \tau_0 \) is the shear strength of the material. Increasing the shear stress, reducing the normal stress, or increasing the pore-fluid pressure, will all bring a fault to failure. These stress changes can be caused through direct or indirect changes. Mass or volume changes from injection, extraction, or loading of material, can change the local stresses acting on a nearby fault and induce seismicity. Failure can also occur through direct pore-fluid pressure changes along a fault through fluid injection, however this mechanism requires a high permeability pathway from the source of injection to the fault. In intracontinental regions, where critically stressed faults exist within the present day stress field, stress changes related to industry activities such as fluid injection can reduce the effective normal stress enough to induce seismicity.

Wastewater disposal induced seismicity raises the pore-fluid pressure on a fault through direct fluid contact with the fault. Seismicity is thus related to the time it takes for a critical level of fluid pressure to be transmitted from the injection well to a critically stressed fault, and will continue until the pore-fluid pressure on the fault diffuses to a sub-critical level, which can be up to years after injection has ceased.

Hydraulic fracturing induced seismicity occurs on shorter timescales, so the mechanics of stress and pressure changes are slightly different than in disposal cases. While there is likely a component of increasing pore-fluid pressure during hydraulic fracturing, because hydraulic fracturing occurs in low permeability reservoirs, the increased pressure is generally confined to the stimulated interval. Elevating the pressure in the formation during hydraulic fracturing is thought to change the poroelastic stresses, increasing the shear stress acting on nearby critically stressed faults, which accounts for the almost instantaneous stress changes and seismicity seen in these instances.

2. Data and Analysis

An initial catalog of seismicity in the study area was obtained from Frohlich 2012, in the J-A region (Figure 1b). Optimized waveform template matching (Skoumal et al., 2015a, 2015b; Skoumal et al., 2014) was performed using all cataloged seismicity as templates and TA station recordings from 134A, 135A, and 234A from November 2009 – October 2011. Matches were filtered to network normalized cross-correlation coefficient (NNCC) > 12*MAD. Events were relocated using waveform cross-correlation and hypoDD with TA stations 134A, 135A, 137A,
234A, and 237A (Waldhauser, 2001), and a refined velocity model for the eastern Fort-Worth Basin (Frohlich et al. 2010; Enercon Services, Inc., 2009). Double difference relocations were based off of template hypocenters as cataloged in Frohlich 2012, where event depths were fixed at 5 km.

Magnitudes were calculated using a Richter scale approach:

\[ M_L = \log \left[ \frac{A}{A_0} \right] \]

For each template event the median scale factor \( A_0 \) was calculated based on cataloged magnitudes and S-wave amplitudes \( A \). For matched events, magnitude was calculated using \( A_0 \) and the S-wave amplitudes at each station and component, with the median value being the final magnitude. For events that matched with multiple templates, the template with the highest NNCC was used.

Monthly injection intervals, volumes, and pressures from wastewater disposal wells were obtained from the Texas Railroad Commission (TXRRC). We were unable to find a complete database of hydraulic fracturing stimulation reports for Johnson County, TX between 2009-2011. FracFocus has been useful as a resource for obtaining hydraulic fracturing stimulation dates and times in other regions of the U.S., however because operators were not required to report to until mid-2011, this database was incomplete over the study period. The TXRRC completions query contained reports for some wells, however was missing entries for most of the wells in the region. Additionally, there were some inconsistencies between completion dates listed in the query and in other areas on the TXRRC website and FracFocus. The lack of complete data on stimulation dates for wells in Johnson County led us to rely on well production data to estimate the timing of well stimulation to within a few weeks up to a few months prior to the well production start date. Hydraulic fracturing wells with production start dates between 2008 and 2012 were identified to determine possible time windows of well stimulation to correlate temporally and spatially with seismicity.

Stratigraphic horizons and depth to basement in the study area were estimated from structure contour and isopach maps (TWDB, 1972). The Precambrian basement-Paleozoic cover contact was additionally estimated to be deeper than the base of the deepest disposal well in the region, based on publically available geophysical well logs.
3. Results

3.1. Temporal Catalog

Waveform template matching identified 977 unique matches from the combined set of templates over the 2-year time period (Figure 2). The improved temporal catalog shows a constant background level of seismicity (M\textless{}1) throughout 2010 and 2011, and highlights several distinct spikes in activity, the densest cluster being in June 2011, with smaller clusters in December 2009, May 2011, and July 2011. Total monthly injected volumes from all nine disposal wells increased from 14.92x10^5 bbls in late 2009 to 22.34 x10^5 bbls in late 2011.

The overall increase in seismicity, and constant background seismicity seen throughout the study period, is consistent with an increase in injected volumes, and known patterns of wastewater injection induced seismicity. Previous studies of wastewater injection induced seismicity show seismicity occurring on timescales of weeks, up to months, and even years (e.g. Healy 1968, Ake 2005) after the initiation of injection, consistent with our current observations. However, there is no correlation between the injected volumes and the sudden bursts of seismicity. With only monthly injection data publically available, detailed analysis of the controls of wastewater disposal on seismicity is not possible. To further understand the causes contributing to these distinct spikes in seismicity, a detailed characterization of the temporal patterns is necessary. For this purpose, the following discussion will be focused on the largest of these spikes, in June 2011.

3.2. June 2011 Sequence

Between June 5\textsuperscript{th}-11\textsuperscript{th}, 443 events were detected with a maximum magnitude of 2.4. June 7\textsuperscript{th} had the densest spike in seismicity, with 168 events occurring in 24 hours. The temporal pattern seen in June shares many characteristics with recognized sequences of hydraulic-fracturing-induced seismicity as documented in Ohio (Skoumal et al., 2015a, 2015b). These characteristics are (1) HF induced swarms occur on much shorter timespans compared to WWD induced swarms, over the course of hours to days, as opposed to weeks or months, (2) seismicity doesn’t follow a mainshock aftershock pattern, rather, the largest event in the swarm commonly occurs towards the end of the sequence, (3) seismicity occurs in short bursts, often aligning with individual stages of HF stimulation (however seismicity does not necessarily only occur during stimulation), and (4) there are no detected events leading up to the spike in seismicity. A
hydraulic fracturing induced swarm in May 2014 in Belmont County, OH (Figure 3a), an area with no previously documented seismicity, exhibited these four characteristics. The swarm lasted four days, with seismicity occurring in pulses lining up with individual stages of hydraulic fracture stimulation, and culminating in a $M_L \sim 2$ event halfway through the sequence. These characteristics can also be seen in the June 2011 Johnson County cluster (Figure 3b): the entire sequence occurred over 5 days, with seismicity occurring in distinct spikes over time spans of a couple hours. The largest magnitude event, $M_{2.4}$, occurred towards the end of the sequence on June 7th, with seismicity rapidly tapering off after this event, and there were no recorded earthquakes in the week prior to the start of the sequence. The similarity between these two swarms means that hydraulic fracturing needs to be considered as a potential cause of the seismicity in the region.

A Gutenberg-Richter b-value of 1.41 using the least squares method and 1.19 using the maximum-likelihood estimate was calculated for the June 2011 sequence (Figure 4). B-values for the entire sequence of seismicity from 2009-2011, not including the events of June 2011, were 1.02 and 1.06 using least squares and maximum-likelihood respectively. While natural earthquake sequences are expected to follow a b-value=1, previous work has shown seismicity during hydraulic fracturing to have a b-value $\sim 2$ (Maxwell, 2009; Wessels, 2011) as compared to injection induced seismicity which is expected to have a b-value $<1$ (Bachmann et al., 2014; Lei et al., 2008). A higher b-value indicates more smaller magnitude events than expected. The relatively large b-value associated with the June 2011 sequence as compared to the background seismicity potentially points to an association with hydraulic fracturing.

While detailed well completion dates and times are not publically available from the TXRRC, monthly production values from horizontal wells provide precision down to a month of when an individual well went online. Figure S1 shows horizontal wells that began producing between May and September 2011. Even though these data do not provide stimulation dates, they can be used to say that hydraulic fracturing was prevalent during the June 2011 sequence, and that numerous active wells were located within 5 km of earthquake epicenters. Because of a potential temporal correlation with seismicity, in addition to a known spatial correlation, HF cannot be excluded as a possible factor contributing to the increase in seismicity in Johnson County.
4. Discussion

4.1. Fault Trends

Cataloged events from June 2011 along with hypoDD locations on matches from the most productive template in the June sequence, template 027 (2011-06-07T00:27:55), locate along a NE-SW trend (Figure 5), and at depths of 4 to 7 km (Figure 6). Bootstrapping results reveal relative location uncertainties of 2σ=160m in the vertical direction and 2σ=90m in the horizontal direction. Relocations using hypoDD on matches from other June and July 2011 templates show similar fault trends to that derived from the most productive template 027, with the sequences located up 2 km apart (Figures S2 and S3). The local network was sparse during this time frame so the absolute location of each of the templates, as well as the locations of its matches, has a level of uncertainty associated with it. However, the consistency in fault trends across the three sequences suggests that the patterns of seismicity accurately represent the faulting in the region. The focus here will remain on the results from template 027, as it is the most clustered sequence based on the strong waveform similarity and larger number of events.

Seismicity from template 027 occurs at depths between 4-8 km within the crystalline basement and close to the basement-cover contact. A cross sectional view of seismicity (Figure 6) outlines a fault plane spanning ~4 km in depth within the Precambrian basement, and relative depth uncertainties of 160 m mean that the vertical span of seismicity is real. While the hydraulic fracturing process inherently produces seismicity, it is generally contained within the production interval, and limited to microseismicity M~<1 (Warpinski et al., 2012). All of the seismicity found is located in the crystalline basement, a few km deeper than the production interval, and many of the matched events have M>1.0. These observations support the hypothesis that seismicity is occurring on reactivated, pre-existing, critically stressed faults. The fault trend is consistent with the orientation of critically stressed faults in the regional present day S_Hmax of ~N040°E (Tingay et al., 2006; Frohlich et al., 2010; Lund Snee & Zoback, 2016), as well as with the predominant orientation of regionally mapped faults in the FWB (Ewing, 1990). Faulting in the FWB tends from predominantly normal, to predominantly strike slip, moving from South to North, with Dallas Fort-Worth marking the transition zone from normal to strike slip movement. These geometries are evidenced through examples in Venus (Frohlich et al., 2016), Azle (Hornbach et al., 2015), and Hamilton County (Khatiwada et al., 2013), all of which display normal-sense displacement. The Ellenburger Group, in addition to being a highly karsted
interval, has pervasive collapse features related to basement-involved normal faults (Sullivan et al., 2006). These features provide a possible pathway for the injected fluids at the well to influence the stresses on nearby preexisting basement faults.

Many of the presently mapped faults in the region have orientations that are critically stressed in the present day stress field, and numerous previous studies have shown extensional faults extending from the basement up through the injection interval. These observations have implications on the overall availability of critically stressed faults in the basin with relative ease of being reactivated through industry activities.

4.2. Controls on Seismicity

Without detailed industry data, hydraulic fracturing cannot be directly correlated with seismicity. However, because of the number of hydraulic fracturing wells operating during this time frame, there are two possible explanations for the temporal patterns of seismicity. (1) Hydraulic fracture stimulation at any number of wells within the study region line up with distinct spikes in seismicity, meaning that there is a temporal as well as spatial correlation with seismicity. (2) Hydraulic fracture stimulation is not temporally correlated with seismicity, meaning that wastewater disposal remains the main control on the increase in seismicity. If this is the case, it would imply that WWD induced swarms can show a similar temporal signature to HF induced swarms as laid out in previous studies. If there were distinct pulses of high volume injection during times of increased seismicity, WWD could theoretically be reactivating faults via transmission of poroelastic stresses, similar to what we would expect in a HF induced case. Because only monthly injected volumes are publically available, and completion dates are unavailable, we cannot differentiate between these possibilities. Either way, in a region with high injection rates, it is undeniable that WWD is influencing the stresses on nearby faults. The uncertainty remains in the extent to which HF is involved, and the fault reactivation mechanisms at play.

5. Conclusions

A reevaluation of seismicity in NE Johnson County during the time of the TA deployment provided a more complete catalog of seismicity, highlighting several temporal patterns necessary for understanding the controls on seismicity in this area. While injection data
show that WWD is likely related to the overall increase in seismicity since 2008, industry data on active hydraulic fracturing wells and temporal patterns of seismicity also point to a possible correlation with well stimulation. Increased b-values of $b_{LSQ}=1.41$ and $b_{MLE}=1.19$ during June of 2011 as compared to $b_{LSQ}=1.02$ and $b_{MLE}=1.06$ during the rest of sequence provide additional support for a hydraulic fracturing influence during this time frame. Without complete data on stimulation dates and times, the degree to which increased seismicity is related to hydraulic fracturing cannot be determined. However, this current analysis indicates that hydraulic fracturing was possibly involved in producing seismicity.

Relocated earthquakes detected through waveform template matching follow regional fault trends and geometries, and are consistent with expected orientations of critically stressed faults based on the present day stress field. Many mapped faults in the FWB follow these trends, with basement faulting extending close to the basement-cover contact or through the sedimentary section, and specifically through both injection and production intervals. This has implications on the availability of unmapped, critically stressed faults in the FWB, with the potential to be reactivated based on their location relative to industry activities. Industry cooperation is necessary in order to understand the specific mechanisms related to induced earthquakes, and to determine the best practices to mitigate future hazards in areas with increasing seismic activity.
6. References
The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to seismic waveforms used in this study. The Texas Railroad Commission online database was used for access to industry data.


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7. Figures

Figure 1. (a) Map of the Fort Worth Basin, TX, showing regionally mapped faults (green) (Ewing, 1990), and seismic stations used in this study (black triangles). (b) Detailed study area as outlined by red rectangle in (a). Circles are cataloged earthquakes from Frohlich (2012). Blue triangles are wastewater disposal wells.
Figure 2. Earthquake magnitudes vs time for all template events (red circles) and matches (black circles) with NNCC > 12*MAD. Blue line shows total monthly injected volume from all 9 injection wells in northeast Johnson county.
Figure 3. Earthquake magnitudes vs time for (a) Belmont-Guernsey Co. sequence in Ohio, a hydraulic fracturing induced case (Skoumal et al., 2015b), and (b) Johnson Co. June 2011 sequence. Horizontal bars represent individual stages of hydraulic fracturing stimulation. The spikes in seismic activity in (b) resemble that of (a), where spikes in seismicity line up with individual stages of hydraulic fracturing stimulation.
Figure 4. Magnitude frequency relationships for June 2011 (red) and the background seismicity between 2009-2011 (blue). Gutenberg-Richter b-values are reported as least squares ($b_{LSQ}$) and maximum-likelihood estimate ($b_{MLE}$).
Figure 5. Map of hypoDD relocations of matched events (pink circles) from template 027 (red circle), and focal mechanism of May 2015 M4.0 event from the USGS. Blue triangles are deep disposal wells operating at this time. A-A’ and B-B’ represent cross-sectional lines in Fig. 6.
Figure 6. (A-A’) SW-NE and (B-B’) NW-SE cross sections of template event 027 (red) and hypoDD locations of matches (pink). Blue lines shows waste disposal wells (thicker indicates injection interval). Stratigraphic contacts are shown between the undifferentiated Pennsylvanian-Cretaceous (white), Barnett Shale (green), Ellenburger Group (blue), Cambrian section (gold), and Precambrian basement (tan) (Bruner and Smosma, 2011; TWDB, 1972). Dashed line shows basement-cover contact as estimated from the base of the deepest well.
8. Supplementary Material

8.1 Velocity model

A six layer velocity model modified from Frohlich 2011 was used for earthquake locations. Velocities were taken from Enercon Services, Inc. 2009 for each of the stratigraphic layers, and depths were adjusted to more accurately represent the stratigraphy in northeastern Johnson County. Adjusted depths were taken from published structure contour maps and deep well logs in the study area (Texas Water Development Board, 1972). While stations 137A and 237A were located across the Ouchita thrust front, the change in velocity structure was determined to not significantly alter the locations.

Table S1. Velocity model for the eastern Fort-Worth Basin.

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<th>( V_s )</th>
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</tbody>
</table>
Figure S1. Production start dates by month of horizontal wells in Johnson County. Colored squares show wells beginning production May-Sept. 2011 (orange-May, gold-June, yellow-July, light green-August, green-September). Cataloged earthquakes and wastewater injection wells plotted as circles and inverted triangles respectively.
Figure S2. Map of hypoDD relocations of events from template 031 in June 2011 (catalog: orange, matches: yellow), template 0717 in July 2011 (catalog: dark green, matches: green), and template 027 in June 2011 (catalog: red, matches: pink). Focal mechanism of May 2015 M4.0 event from the USGS. Blue triangles are deep disposal wells operating at this time. A-A’ and B-B’ represent cross-sectional lines in Fig. S3.
Figure S3. (A-A’) SW-NE and (B-B’) NW-SE cross sections of events from template event 031 in June 2011 (catalog: orange, matches: yellow), and template 0717 in July 2011 (catalog: dark green, matches: green). Blue lines shows waste disposal wells (thicker indicates injection interval). Stratigraphic contacts are shown between the undifferentiated Pennsylvanian-Cretaceous (white), Barnett Shale (green), Ellenburger Group (blue), Cambrian section (gold), and Precambrian basement (tan) (Bruner and Smosma, 2011; TWDB, 1972). Dashed line shows basement-cover contact as estimated from the base of the deepest well.