Dallas-Fort Worth earthquakes coincident with activity associated with natural gas production

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On 31 October 2008 and the following day, numerous Dallas-Fort Worth (DFW) residents called 911 to report experiencing several small earthquakes, accompanied by loud booming noises and the shaking of walls and furniture. Using data recorded by regional seismic stations, the USGS National Earthquake Information Center (NEIC) located nine earthquakes with magnitudes between 2.5 and 3.0. On 16 May 2009, this scenario repeated itself, as local residents felt three earthquakes and the NEIC located four (largest = magnitude 3.3). A third sequence of felt events began on 2 June 2009, approximately 65 km southwest near the city of Cleburne, Texas, but has not yet been studied in detail (Figure 1).

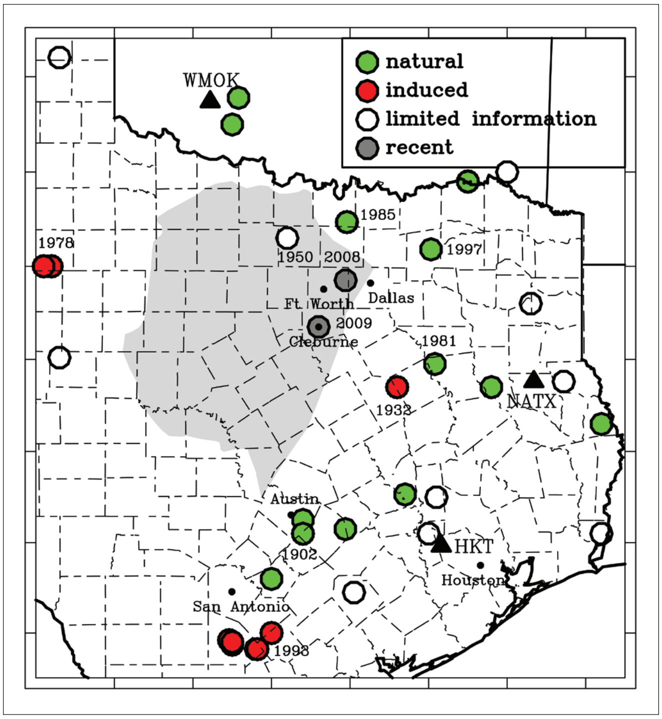

Figure 1. *Map of eastern Texas and, showing historically felt earthquakes (circles) and continuously operating seismograph stations (triangles), and extent of the Barnett shale (shaded area), the focus of increased natural gas production since about 2000. Colors indicate whether earthquakes are of probably of natural origin, induced by human activity such as fluid injection or petroleum production, recent, or origin uncertain. Earthquakes labeled 1902, 1932, 1978, 1985, 1993, 1997, 2008, and 2009 are mentioned in the text.*

For various reasons these earthquakes caused concern locally and induced a spirited response from the media. News stories raised the possibility that "drilling" to recover natural gas from the Barnett Shale might cause such earthquakes. Tarrant and Dallas Counties, home to Fort Worth and Dallas, respectively, constitute a major urban center with a combined population of about four million, and an underlying worry was that these earthquakes might be harbingers of larger, more damaging events to come.

Following the October earthquakes, seismologists from Southern Methodist University (SMU) borrowed six, three-component, broadband seismographs from an NSF-supported instrument pool and operated them at sites in Tarrant and Dallas Counties (Figure 2) between 9 November 2008 and 2 January 2009. Although the NEIC reported no felt earthquakes during this period, the SMU stations recorded numerous local events, including 11 earthquakes between 20 November and 2 December with exceptionally well-recorded P and S arrivals on three stations, AFDAD, AFMOM, and CPSTX.

The present paper summarizes our analysis of seismograms of the DFW sequence and reports precise locations for 11 well-recorded but "non-felt" events. Using seismological data and other information available in the public record, we show that: (1) In 2008 prior to 29 October, we detected no earthquakes occurring near DFW, including earthquakes too small to be locatable by the NEIC; (2) the 11 hypocenters have a preferred focal depth of 4.4 km and lie along a 1.1-km SW-NE line; and (3) the mean epicenter estimate of the 11 events is less than 0.5 km from a 4.2-km deep saltwater disposal (SWD) well where injection began on 12 September 2008, seven weeks before the DFW focus became active. On the basis of time and spatial correlations, we conclude the DFW sequence may be the result of fluid injection at the SWD well, but we are puzzled as to why earthquakes occur at this particular location but not near other SWD wells in the region. Finally, we discuss the DFW earthquakes in the context of regional historical seismicity, which includes both natural and induced earthquakes. We observe that historical induced earthquakes in the Texas region have all been less than magnitude 4.6 and have not produced substantial damage.

When quakes occurred

Locating an earthquake requires knowledge of P and/or S arrival times at three or more stations; however, for the DFW sequence, the seismograph station at WMOK at Wichita Mountain, Oklahoma, (Figure 1) recorded numerous signals from earthquakes similar in wave shape to, but smaller than, the 13 earthquakes locatable by the NEIC. Station WMOK, part of the National Advanced Seismic System, is a continuously operating three-component, broadband station situated 262 km northwest of DFW. To evaluate the time history of DFW activity, we cross-correlated the broadband signal at WMOK with one of the located DFW earthquakes. We then visually inspected all identified events with amplitudes corresponding to magnitude 1.5 or greater and having a cross correlation exceeding 0.4. Nearly all such events had identi-

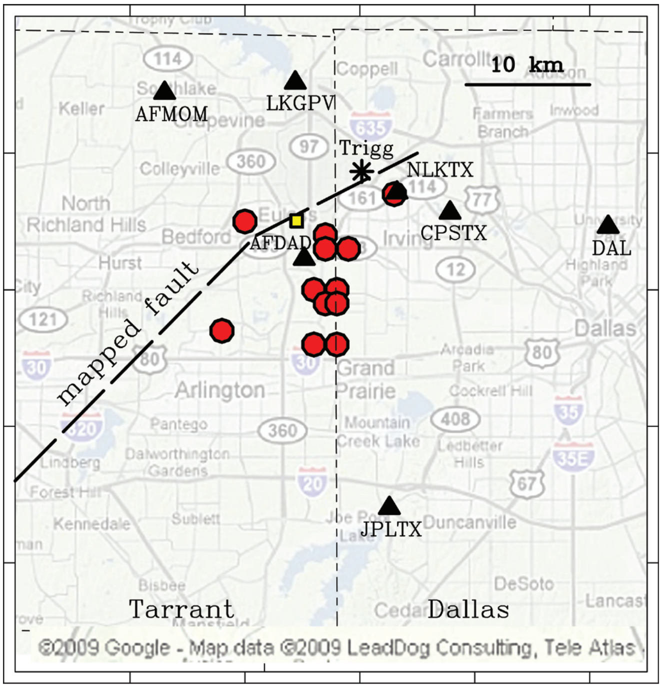

Figure 2. *Map of boundary between Tarrant and Dallas counties, showing epicenters (red circles) reported by the NEIC between 31 October 2008 and 16 May 2009, 1-km square area (yellow square) containing all epicenters determined in this paper, and locations of seismograph stations (triangles) deployed temporarily by SMU. Also shown are locations of Trigg Well 1 (center) and the down-to-the-south normal fault mapped by the Texas Bureau of Economic Geology (thick dashed line).*

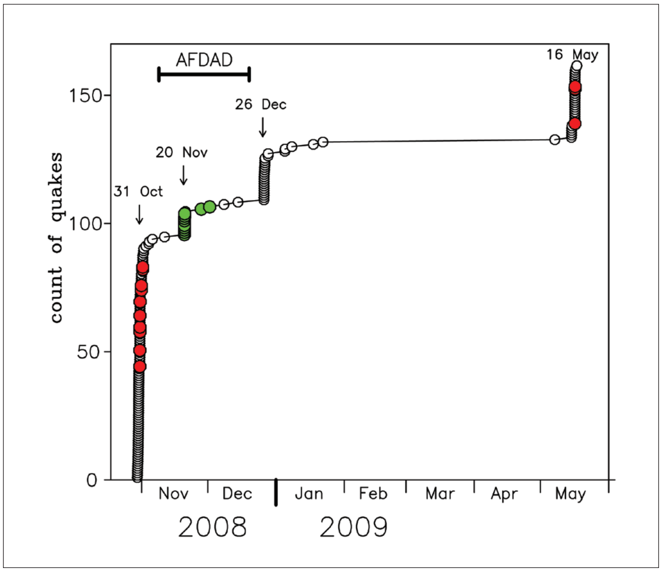

Figure 3. *Time history of earthquake activity at the DFW focus as determined by analysis of seismograms at station WMOK. Circles show cumulative number of events identified. Red circles are earthquakes reported by the NEIC; green circles are earthquakes recorded by the SMU network and located in this study. Bar at upper left indicates period when closest station AFDAD was operational.*

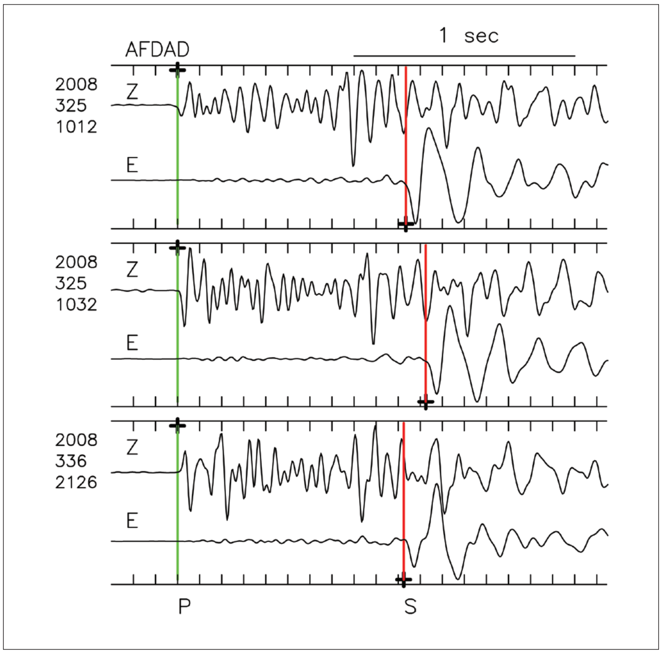

Figure 4. *Examples of vertical (z) and east-component seismograms recorded at station AFDAD, aligned with the P arrivals (green). Note that the first motions on the vertical component are not all the same, and that S arrivals (red) differ by as much as 0.1 s.*

fiable P onsets and impulsive S phases with a characteristic coda shape; (S-P) time intervals were all ~30.75 s.

This analysis of the WMOK record (from 1 January 2008 to 30 August 2009) identified 179 small-magnitude earthquakes that apparently originated from the DFW focus (Figure 3). None of these earthquakes occurred prior to 0101 on 30 October 2008, when a magnitude 1.7 event occurred; the last event identified (magnitude 1.8) occurred on 17 May 2009 at 1312. The majority of identified events cluster within four discrete time periods; 100 occurred between 30 October and 1 November; 11 on 20 November; 18 on 26 December; and 28 on 15–17 May.

Where quakes occurred

We picked P- and S-arrival times for events recorded by the SMU temporary network (Figure 2) by lining up identifiable features on incoming arrivals; because the sampling interval was 0.005 s and because the phases were impulsive, we estimate these picks have a relative accuracy of ~0.02 s (Figure 4). Whenever possible we read arrival times at three remaining stations (LKGPV, JPLTX, and NLKTX); however, these stations were less sensitive and the accuracy was poorer than the three primary stations.

To locate the earthquakes, we first used a conventional constant-velocity crustal layer model algorithm. Velocity interval information was taken from Trigg Well 1 (Figure 5), ~6 km east of the DFW focus. We thus specified three layers: a surface layer (V_P = 2.9 km/s, thickness = 600 m) representing Cretaceous strata; a second layer (V_P = 4.0 km/s, thickness = 2.15 km) representing Pennsylvanian strata; and a third layer (V_P = 6.3 km/s) of Ordovician and older strata. V_P/V_S was fixed at 1.87 in all layers as constrained by the relative S and P times of the 11 earthquakes. The hypocenters we determined for the 11 well-recorded earthquakes were highly consistent

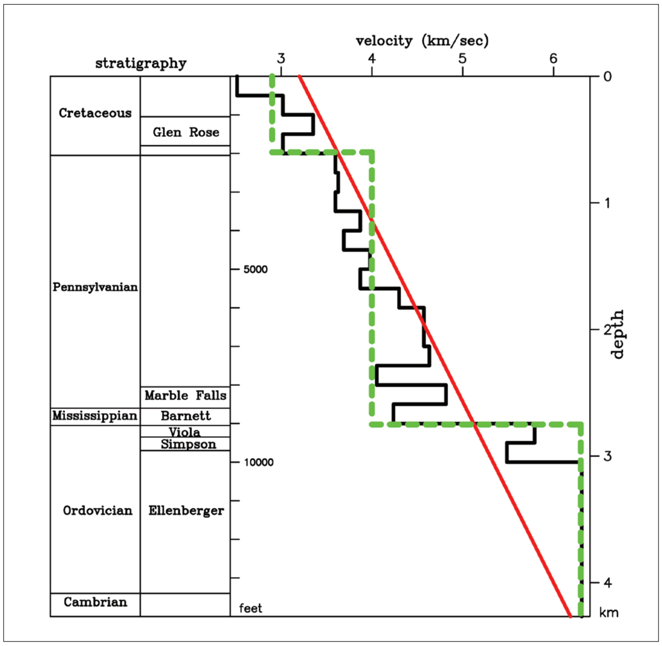

Figure 5. *Interval velocities and stratigraphy reported by Geotechnical Corporation for Trigg Well 1 (black line), and velocity models used to constrain hypocentral locations (solid red line and dashed green line).*

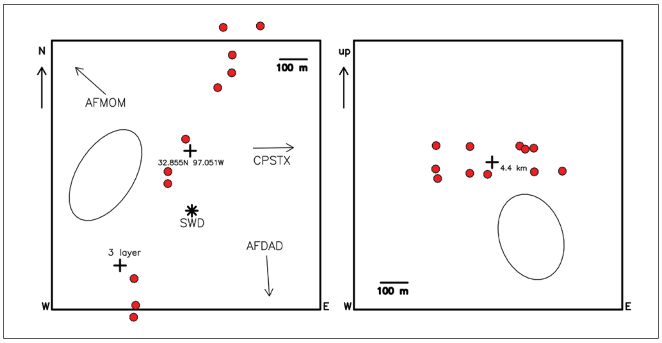

Figure 6. *Map (left) and cross section (right) showing precise relative locations (solid circles) for 11 well-recorded earthquakes detected at the SMU network. Solid line forming boundary of map corresponds to 1-km yellow square in Figure 2. The ellipsoids indicate the uncertainty in the relative locations; star labeled SWD is location of salt-water disposal well. Solid borders enclose a 1-km square area. Hypocentral positions and SWD location are plotted relative to the mean location of 11 events at 32.855°N, 97.051°W, 4.4 km depth (+ symbol) determined using linear velocity model in Figure 5. Plus (+) symbol labeled "3 layer" indicates how mean location shifts when locations are determined using a three-layer velocity model.*

with this model, as the rms difference between observed and calculated traveltimes ranged from 0.02 to 0.06 s. The mean of the 11 locations was just south of the Dallas-Fort Worth Airport, at 32.852°N, 97.054°W, and depth of 4.8 km.

To assess the sensitivity of the location to the velocity model, we also located the 11 well-recorded earthquakes using a velocity model that increases linearly with depth (z), since inspection of the Trigg well data suggested this fits the interval velocity better than do constant-velocity layers. Assuming V_P = 3.2 + 0.7z km/s (units of z are km) placed the mean location for DFW focus at 32.855°N, 97.051°W, and

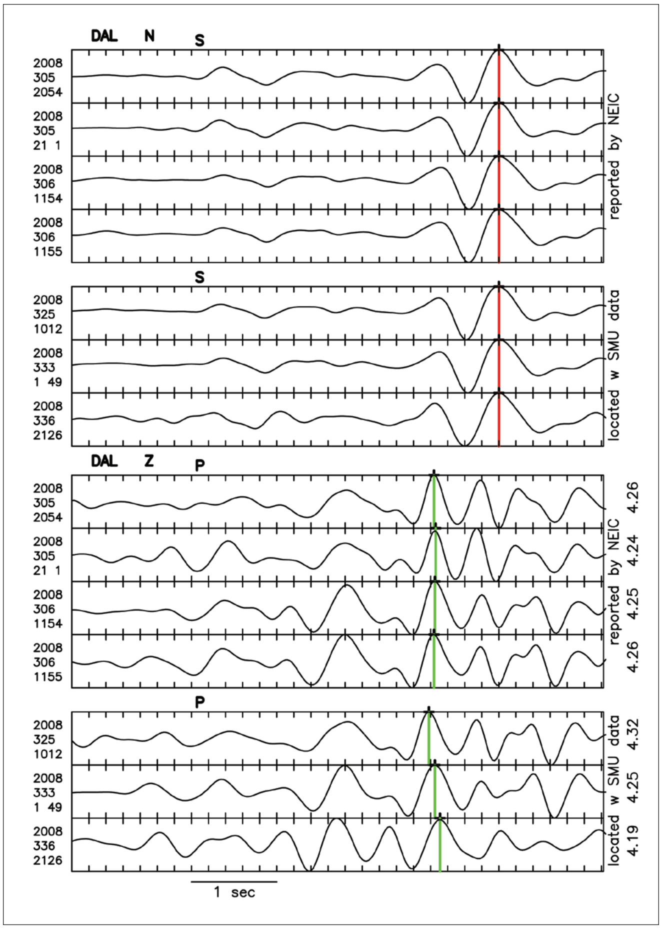

Figure 7. *S and P arrivals recorded at station DAL from four earthquakes reported by the NEIC and three located using data from the SMU temporary network. The "S" and "P" labels indicate the approximate times of emergent S and P arrivals on the N-component (top two panels) and vertical (z) component (bottom two panels); the plus (+) symbols about 2.5–3.0 seconds later are higher-amplitude coda arrivals whose arrival times can be picked precisely. All signals are aligned with the high-amplitude S-coda signal (red line, top two panels); labels at left indicate origin times of the earthquakes; labels at right are the time differences between the marked S-coda and P-coda (green line) arrivals. Note that the P-coda arrivals vary by 0.13 s and less, indicating that (S-P) intervals at DAL are nearly the same for quakes located by NEIC and those located in this study.*

depth of 4.4 km. This is about 435 m northwest of the three-layer location above.

Assuming the mean location to be correct, we determined precise relative locations for the 11 non-felt earthquakes recorded by the SMU network (Figure 6). These relative locations indicate that all 11 earthquakes occupy a region with horizontal dimensions of about 1100 m and within a depth range of 125 m. Three observations support the conclusion that the events are at different foci despite the high waveform correlation at stations such as WMOK. First, location simulations assuming reading errors of ±0.02 s shift the locations by only about ±200 m horizontally and ±125 m vertically, significantly less than the variation observed among the actual locations. Second, close visual inspection of the seismograms indicates that (S-P) intervals are not identical at individual stations, e.g., at AFDAD (S-P) varies by as much as 0.1 s. Third, visual inspection of seismograms at individual stations indicates that waveforms are not all identical, suggesting that their locations and/or focal mechanisms differ (Figure 4).

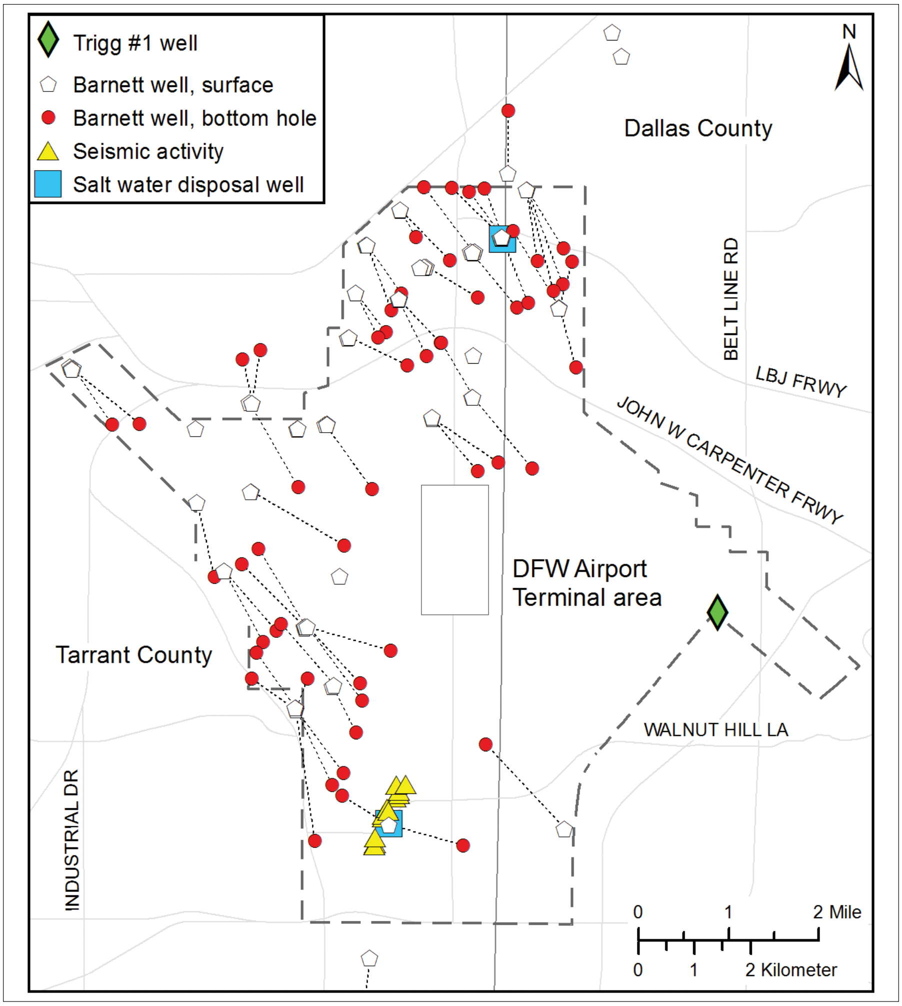

Figure 8. *Map of region surrounding DFW airport, showing locations of earthquakes, producing Barnett Shale gas wells, SWD wells, and Trigg Well 1. Dashed line outlines DFW airport property.*

Our location methods place the small DFW earthquakes recorded during the portable deployment along a NE-SW line just south of the Dallas-Fort Worth airport. These locations are 2-10 km northwest of most locations reported by the NEIC for the larger earthquakes of 31 October, 1 November, and 16 May which were not recorded by the SMU temporary network. However, systematic location errors of 10 km or more are typical for small earthquakes located by the NEIC using distant regional stations and an average regional velocity model. The NEIC epicentral locations are only estimates, and the reported depths are usually fixed arbitrarily as they are poorly resolved.

Although the SMU temporary network recorded none of the earthquakes felt by DFW residents and reported by the NEIC, observations suggest that the NEIC earthquakes originated from nearly the same region as the 11 earthquakes (Figure 6) recorded by the SMU network and located precisely in this study. At station WMOK, (S-P) intervals for both the NEIC-reported and SMU-recorded earthquakes were all ~30.75 ± 0.12 s, with the observed range in (S-P) intervals (~0.2 s) being approximately equivalent to the picking uncertainty for the P arrival.

We also analyzed signals recorded at station DAL (Figure 2) on the SMU campus about 25 km from the DFW focus. Seismograms at DAL weren't useful for routine locations as neither P nor S arrivals for DFW earthquakes are impulsive; for both phases the strongest signal arrives in the coda about 2-3 s after an initial emergent arrival. We thus aligned the signals with the high-amplitude peak in the S coda and compared relative arrival times for the high-amplitude peak arrivals in the P coda (Figure 7). The range in arrival time differences was 0.13 s, which corresponds to a station-to-epicenter variation of about 800 m. Thus the data recorded at DAL are consistent with the assertion that the SMU-recorded and the NEIC-located earthquakes originate from nearly the same focus.

Relationship to gas production and regional geology

The production of natural gas from shale involves four activities that conceivably could affect stress locally and/or induce seismic activity. These are drilling wells, hydraulic fracturing, the removal of gas and other fluids during production, and saltwater disposal.

Although the Barnett Shale of the Fort Worth Basin has produced significant amounts of natural gas since 2001, prior to 2002 there were few drilled wells in highly urban Tarrant County. This trend changed partly because of favorable gas prices but also because multistaged hydraulic fracture procedures in horizontal wells made urban production feasible. Between January 2001 and February 2009, 2200 gas wells were completed in Tarrant and Dallas Counties. Within 10 km of the DFW focus there were no permitted gas wells prior to March 2007. Since January 2008, 13 wells have been drilled and hydraulically fractured in the Barnett Shale within 3 km of the DFW focus. These nearest wells began production on dates ranging from June 2008 to March 2009. To dispose of brine recovered in the early phases of production of these and other Barnet wells, two salt-water disposal (SWD) wells were also drilled, one northeast and one southwest of the DFW airport.

The southwest SWD well is about 200 m south of the mean DFW focus as determined using the linear velocity

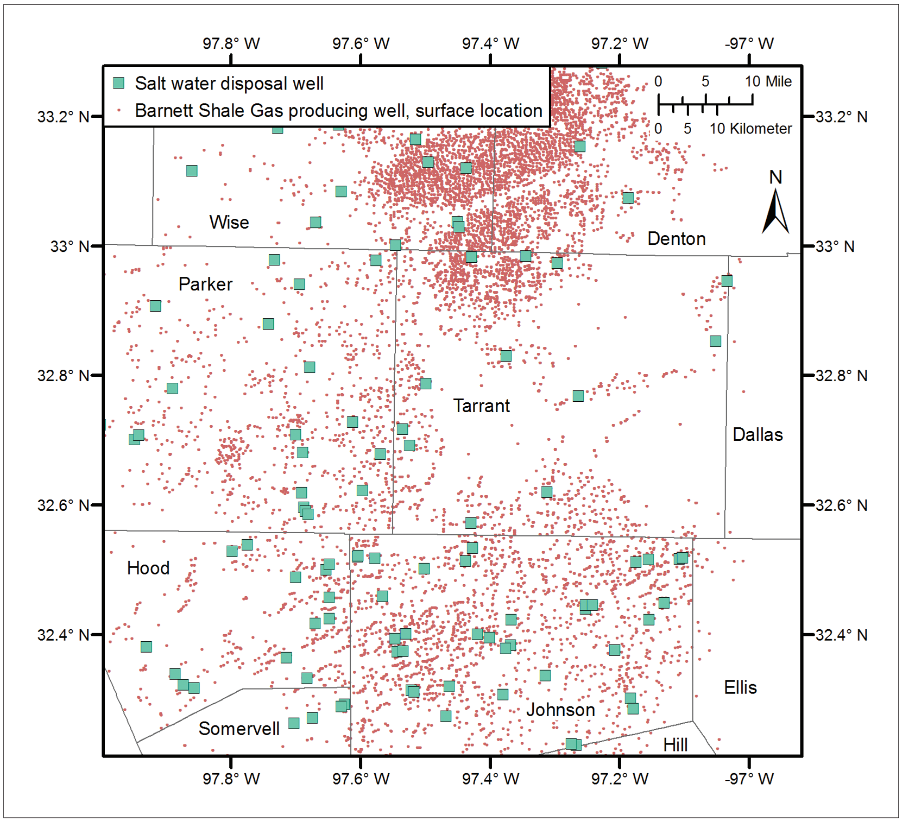

Figure 9. *Map of producing natural gas wells and SWD wells in Tarrant and surrounding counties.*

model (Figure 8), much closer than any of the production wells where hydraulic fracturing occurred. The permitted injection interval (10,752-13,729 ft or 3.3–4.2 km) is in the Ellenberger Formation, only slightly shallower than the focal depths we determined for the well-recorded earthquakes. Permits filed with the Texas Railroad Commission indicate that drilling for the SWD well commenced on 23 December 2007 and finished on 22 March 2008.

Injection at the southwest SWD well commenced on 12 September 2008, seven weeks before the first DFW earthquakes occurred. Brine injection volumes averaged 8000-11,000 b/d from October 2008 through June 2009, and injection was terminated in August 2009. These rates are similar to rates reported at other locations where no earthquakes occurred; reports filed with the Texas Railroad Commission for the SWD well northeast of the DFW airport indicated that brine injection volumes for January-March 2008 averaged about 9000 b/d. A survey of nearby SWD wells in Tarrant and Johnson Counties found rates ranging from 100,000-500,000 b/month, indicating that 10,000 b/d is not unusual.

The state tectonic map prepared by the Texas Bureau of Economic Geology shows a northeast-trending normal fault in the subsurface that intersects the Dallas-Tarrant county line approximately at the location the DFW focus (Figure 2). The map indicates the vertical offset on this fault at the Ordovician Ellenberger level is about 80 m, down to the southeast. Various publications indicate that the present-day maximum principal stress direction in most areas of the Fort Worth Basin is vertical, and the maximum horizontal stress direction is N40°–47°E. Thus, regional stress is favorably oriented to reactivate normal-faulting motion along the mapped fault, and the trend of the epicenters is approximately consistent with seismic motion along such a reactivation.

Discussion

Were the DFW earthquakes natural or triggered by activities associated with natural gas production, most likely saltwater injection to dispose of brines? The spatial and time correlations are consistent with an induced or triggered source. Prior to 31 October 2008, there had been no local felt earthquakes known in Dallas and Tarrant Counties, which have been settled since about 1850. About seven weeks before the DFW quakes began, injection commenced in a SWD well only a few hundred meters from DFW epicenters and with an injection depth of 3.1–4.1 km. This approaches the 4.4–4.8 km we determined for the 11 earthquakes recorded by the SMU temporary local network. These earthquakes and the SWD well are within about 1 km of a mapped subsurface fault which trends in nearly the same direction as the alignment of epicenters. Fluid injections between 200,000 and 300,000 b/month into other faulted areas have triggered small earthquakes and are reported in the literature, recently in Paradox Valley Colorado. It is plausible that the fluid injection in the southwest SWD well could have affected the in-situ tectonic stress regime on the fault, reactivating it and generating the DFW earthquakes.

Elsewhere in central and northeast Texas, natural earthquakes occur (Figure 1), but there are also numerous earthquakes associated with, and possibly related to, petroleum production. Examples of earthquakes of tectonic origin include a 1902 magnitude 3.9 event near Austin, a 1985 magnitude 3.4 earthquake near Valley View (75 km north of the DFW quakes), and a 1997 magnitude 3.4 event near Commerce (110 km northeast). However, a 1932 magnitude 4.0 earthquake near Mexia occurred directly beneath the very productive Wortham oil field. A sequence of earthquakes with magnitudes as great as magnitude 4.6 in 1978 occurred near Snyder, beginning only after the initiation of a large (25 million b/year) water-flooding project in Cogdell Field. And earthquakes known to occur in Atascosa County near Fashing and Pleasanton (e.g., a magnitude 4.3 in 1993) are possibly induced by gas production.

Fortunately, there is no historical record of large (greater than magnitude 4.6) induced earthquakes in Texas. There are thousands of injection wells in Texas, the vast majority of which produce no felt or instrumentally recorded seismicity. When induced earthquakes have occurred, they are small and produce little or no serious damage; the 1978 Snyder earthquake, for example, broke several windows and caused mirrors and pictures to fall off walls. The fault ruptures for typical induced earthquakes generally are too small to cause much damage; to date the largest DFW earthquake, with magnitude 3.3, probably originated as a slip of about 2 cm on a fault rupture with a diameter of about 225 m.

More than 12,000 wells have been completed in the Barnett Shale of the Fort Worth Basin in the past decade (Figure 9), and all received hydraulic fracture treatments. More than 200 saltwater disposal wells are active in the area of Barnett production. If the DFW earthquakes were caused by saltwater injection or other activities associated with producing gas, it is puzzling why there are only one or two areas of felt seismicity.

Fracture stimulation and saltwater disposal are critical components of the current development strategy for shale gas, which provides a large, relatively clean source of energy that can be tapped until renewable sources become more viable. Enhanced geothermal projects rely on fracturing and fluid injection and have also raised concerns about induced earthquakes. Geological carbon sequestration is one approach being researched to combat global climate change. It involves pumping large volumes of carbon dioxide into targeted geologic formations. To allay public concerns, more needs to be known about how these activities interact with in-situ stresses and possibly affect seismic activity. Energy producers, policymakers, and researchers would all benefit from an improved understanding of induced seismicity.

References

Ake, J., K. Mahrer, D. O'Connell, and L. Block, Deep-injection and closely monitored induced seismicity at Paradox Valley, Colorado, 2005, *Bulletin of the Seismological Society of America*, 95, 664–683.

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

Davis, S. and W. Pennington, Induced seismic deformation in the Cogdell oil field of West Texas, 1989, *Bulletin of the Seismological Society of America*, 1477–1494.

Frohlich, C. and S. Davis, *Texas Earthquakes*, 2002, University of Texas Press.

Hsieh, P. and J. Bredehoft, A reservoir analysis of the Denver earthquakes: A case study of induced seismicity, 1981, *Journal of Geophysical Research*, 86, 903–920.

Montgomery, S., D. Jarvie, K. Bowker, and R. Pollastra, Mississippian Barnett shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential, 2005, *AAPG Bulletin*, 89, 155–175.

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