

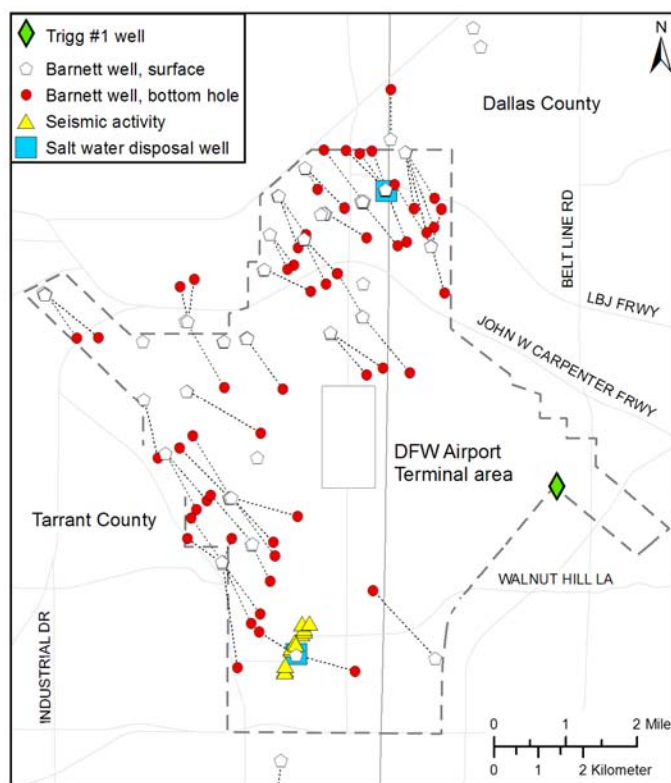
## **Earthquakes Induced by Fluid Injection in Texas and Elsewhere: What Further Research Could Teach Us**

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Between 31 October 2008 and 16 May 2009, Dallas-Fort Worth (DFW) residents felt nine earthquakes with magnitudes between 2.5 and 3.3, and news stories expressed concern they might be caused by ‘drilling’ for natural gas in the Barnett Shale. We have analyzed data collected by temporary local seismograph networks operated in the DFW area in November and December 2008, and near DFW and Cleburne, TX, since June 2009. Eleven of the DFW earthquakes were exceptionally well recorded by the 2008 temporary network, allowing us to determine accurate locations. The events all had focal depths of ~4.5 km and lie along a 1.1 km SW-NE line near the DFW airport property (Figure 1). The mean epicenter is ~0.5 km from a 4.2 km-deep well drilled into the Ellenberger Formation to dispose of brines recovered in flowback operations from nearby Barnett Shale wells. Injection in this well commenced on 12 September 2008, about six weeks before earthquakes first occurred, and continued until August 2009. There is a mapped northeast-trending subsurface normal fault approximately intersecting the earthquake locations. Thus the DFW earthquakes appear to be induced by disposal of produced brines, possibly interacting with a subsurface fault. The earthquakes appear not to be induced by drilling, hydrofracturing, or gas production.



**Figure 1.** Map of DFW airport, showing location of earthquakes (yellow triangles), located by the SMU temporary network, tops and bottom of producing gas wells (white and red symbols, respectively), and salt water disposal wells (blue squares). The DFW earthquakes' hypocenters were situated within less than a km of the bottom of the south SWD well.  
 [Figure reproduced from Frohlich et al., *Leading Edge*, March 2010, p. 273]

Scientists have known for many decades that human activities occasionally induce earthquakes. These activities include fluid injection for disposal or waterflooding; fluid extraction, both for oil and gas production; and the impoundment of surface reservoirs, especially when water depths exceed 100 meters. Recently fluid injection has become of special interest because it is a component of various energy-production-related activities: for the disposal of produced brines in some unconventional gas plays, for waterflooding to enhance oil recovery, for the production of geothermal energy, and for carbon sequestration. These activities enjoy broad-based support—from energy producers, from individuals committed to decreasing U.S. reliance on foreign sources of energy, and from individuals who favor development of solar or wind energy but realize natural gas and geothermal could provide an abundant and relatively clean source of energy while alternatives are being developed.

Although there are ongoing research projects focusing on the relationship between fluid injection and induced earthquakes, the majority of these studies have focused on geothermal energy. Unlike wells in unconventional gas plays, wells to produce geothermal energy are few in number and commonly produce energy at peak capacity for decades; thus geothermal fields are simpler to instrument and study over extended periods before and during production.

We are embarking on a research program focusing on induced earthquakes associated with water disposal activities typical of unconventional gas plays such as the Barnett Shale in Texas' Fort Worth Basin. We have formulated five hypotheses that, if confirmed and/or modified by further research,

would influence the development of strategies for avoiding inducing earthquakes and/or mitigating potential hazards.

• **Hypothesis 1: Induced earthquakes are expected to be no larger than the largest regional natural earthquakes.**

The largest DFW earthquake in 2008-2009 was M3.3 although there have been few historical earthquakes in the region: a natural earthquake of M3.4 occurred in nearby Commerce TX in 1997. A series of earthquakes near Denver, Colorado, culminating in three events with magnitudes of 5.0-5.3 in 1966-1967 are widely acknowledged to be induced by the disposal of fluid wastes by the U.S. Army at the Rocky Mountain Arsenal; in 1882 Denver experienced a natural M6.6 earthquake. A M3.4 earthquake apparently induced by fluid injection in December 2006 near Basil, Switzerland, ultimately led to halting a geothermal project there; Basil had been heavily damaged by a natural M6.5 earthquake in 1356.

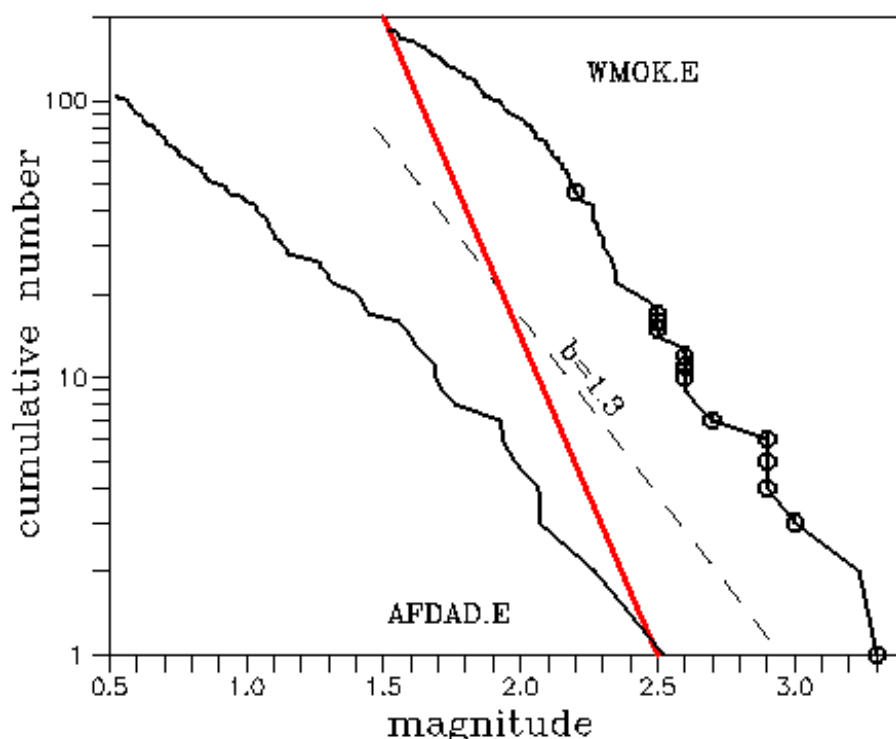
Although there is much evidence in support of this hypothesis, it undoubtedly requires further investigation and possible modification. . The geological constraints or distance that defines the 'region' where an earthquake occurs isn't yet clear. It is also likely that induced quakes having different origins (e.g., fluid injection, fluid extraction, reservoir impoundment) may follow different physical relationships.

• **Hypothesis 2: Larger (>M2.5) induced earthquakes are physically distinct from hydrofrac-induced microseismicity.**

Although hydrofracturing fractures rock and thus technically causes small earthquakes, several features of the larger earthquakes induced by fluid injection indicate that their origin is not hydrofracturing; i.e., they are a different physical phenomenon. That is, they are not frac jobs that got out of control, or indeed related to hydraulic fracturing at all. For example, they exhibit differences in the relative proportions of large and small earthquakes, measured by earthquake seismologists by a statistic called the b-value. In the Fort Worth Basin's Barnett Shale, seismic signals induced by hydrofracturing typically have b-values of 2.0-2.5; sequences of induced earthquakes generally have b-values of 1.0-1.3 (Figure 2).

• **Hypothesis 3: Small (~M2.5-M4.0) intraplate earthquakes often represent release of regional tectonic stress along 'favorably oriented' regional faults.**

The 2008-2009 DFW earthquakes occurred within about a kilometer of a NE-SW trending subsurface fault. Regional tectonic stress measurements indicate that the maximum stress direction is vertical and maximum horizontal stress direction is NE-SW, favoring normal-faulting slip on a NE-SW fault. However, subsurface fault information is unavailable near many small regional earthquakes, and focal mechanism information is also often lacking as a result of the paucity of seismic observations. For small intraplate earthquakes, a systematic review of subsurface fault and regional tectonic stress information would provide a basis for further refining this hypothesis.



**Figure 2.** Magnitude distribution of DFW earthquakes as recorded at two stations WMOK (Wichita Mountain, OK; distance 260 km) and AFDAD (temporary local station; distance 3.5 km). Identification as a DFW event as well as event magnitudes and scalar moments are determined as described in the text. Circles indicate magnitudes of events reported by the USGS. Note that the  $b$ -value (slope of log-number versus magnitude curve) is about 1.3. Red line, with slope of 2.3 indicates approximate reported slope of magnitude distribution for microseismic signals induced by hydrofrac jobs in the Barnett Shale.

- **Hypothesis 4: Larger ( $>M2.5$ ) induced earthquakes often occur when ‘favorably oriented’ regional faults are situated relatively close to (within a few km of) high-volume injection wells.**

The 2008-2009 DFW earthquakes occurred within about a kilometer of both a salt-water-disposal well and the above-mentioned subsurface fault. However, there are literally thousands of active injection wells in Texas, and for nearly all of them there is no publicly available information about subsurface faulting, even those near locations where earthquakes have occurred. Often organizations that hold the permits for injection wells do have detailed information about subsurface geology.

It would be advantageous to undertake a survey of the depths and orientations of subsurface faults (or their absence) near injection wells, including wells that do and do not induce felt earthquakes. If such a survey demonstrated that “aseismic” wells were generally sited well away from subsurface faults, this would be critical information for planning injection projects, particularly in populated areas. Clearly, such a survey is feasible only if researchers have limited access to information about subsurface geology, which is often proprietary. We would like to collaborate with organizations that have proprietary data and share an interest in these problems.

- **Hypothesis 5: Small earthquakes (M~2), both natural and induced but too small to be noticed, occur quite regularly in Texas and many unconventional gas play environments; in most cases they don't represent a hazard—they are a normal, harmless natural phenomenon.**

Earthquakes occur in every state of the U.S., although in many states the largest historically reported earthquakes are small (M4.0 or less). Moreover, the density of continuously recording seismographs is so low in many states (such as Texas) that earthquakes of M3.5 or smaller often go unreported unless they occur in heavily populated areas. Yet, seismicity research demonstrates that small earthquakes are more common than large ones; for a region with a b value of 1.0, for each M4.0 earthquake there are 10 M3.0 earthquakes, 100 M2.0 earthquakes, 1000 M1.0 earthquakes, etc. This suggests that even regions like eastern Texas experience numerous small earthquakes, such as M2 or smaller, every year.

There are many benefits to operating dense regional seismograph networks to monitor small-magnitude earthquakes in regions where society plans injection projects to promote petroleum production, geothermal energy production, or carbon sequestration. These networks are likely to detect small earthquakes regularly; these data support arguments to regulatory agencies and/or to the public that small earthquakes are common and harmless. When earthquake swarms or larger earthquakes do occur, the network data make it possible to identify the source and, if necessary, take appropriate action. For the 2008-2009 DFW earthquake sequence, it wasn't initially possible to pinpoint the locations accurately because USGS-reported locations in this region typically have uncertainties of about 10 km. After a dense local network was installed these data indicated that earthquakes occurred close to a particular salt water disposal well. The earthquakes activity virtually ceased after injection at the well stopped.