Pinning Down the Relationship Between Induced Earthquakes and Injection Well Locations

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1. Induced Seismicity Summary:

Subsurface fluid injection has been recognized to trigger earthquakes (Wesson, 1990). This conclusion is not a recent one. The paper, “An Experiment in Earthquake Control” by C. B. Raleigh et al (1976) documents triggered earthquakes at the Rangely Colorado Oil Field. Unusual earthquakes had been documented at the Rangely Oil Field since 1962. While triggered seismicity cases have been documented for the past half-century, an increase in US oil and gas production over the past decade has made triggered seismicity more conspicuous (Yergin, 2012). The increase in domestic production is largely fueled by innovations in hydraulic fracturing (hydrofracking) techniques. Hydrofracking is the processes of fracturing subsurface rocks with high-pressure fluid injection. Subsequently fractured rocks enhance the release of oil and gas for recovery. Hydrofracking produces waste fluid as a byproduct (Horton, 2012). The waste fluid is disposed of via continuously pumping underground injection wells. Triggered seismicity cases near population centers, such as the Youngstown Ohio case, have attracted national attention.

The mechanism by which fluid injection triggers seismicity is generally understood. As outlined in the 2002 paper “Case Histories of Induced and Triggered Seismicity”, injecting fluids into the subsurface raises the pore pressure of rocks around the injection point (McGarr et al., 2002). An increase in pore pressure effectively decreases normal stresses acting on fault surfaces. Normal stress acting on a fault surface creates friction and is responsible for locking a fault in place. Ultimately, if normal stress is decreased enough, a fault will succumb
to shear stress and slip. The relationship between normal stress, shear stress, and pore pressure is represented by the line equation:

\[ \sigma_s = \mu(\sigma_n - \phi) + c \]

**equation 1:** \( \sigma_s \) = shear stress, \( \mu \) = coefficient of friction (material property), \( \sigma_n \) = normal stress, \( \phi \) = pore pressure within fault zone, \( c \) = cohesion

Equation 1 is known as the Mohr-Coulomb failure criterion. \( \sigma_s \) represents the shear stress required for fault failure. If \( \sigma_s \) is larger then \( \mu(\sigma_n - \phi) + c \), fault slip occurs. Increasing \( \phi \), by fluid injection or other means, decreases the shear stress required for fault failure (McGarr *et al.*, 2002).

While the general mechanisms for triggering seismicity via fluid injection are well documented, predicting when and where triggered seismicity will occur is still difficult. As the national number of fluid injection wells increases, a better understanding of the spatial and temporal relationship between earthquakes and fluid injection becomes important for two reasons. The most important reason is risk assessment. The increasingly prevalent use of fluid injection for waste fluid disposal and hydraulic fracturing presents a potential hazard to proximal urban populations. Understanding when and where fluid injection triggered seismicity will likely occur will help quantify the potential hazard for humans living near injection wells. The second reason is that studying fluid injection triggered seismicity can be insightful for understanding natural earthquake processes such as nucleation (McGarr *et al.*, 2002). Increasing awareness and concern over induced seismicity creates a valuable scientific opportunity for studying earthquakes.

In order to study the relationship between fluid injection and triggered seismicity, data is needed for both earthquakes and injection wells. However, limited data availability for injection wells hampers the study of triggered seismicity. Currently, no database of injection
wells exists on a national scale. Considering the currently poor state of available injection well data, the purpose of this paper is twofold. The first purpose is to examine data needs with respect to creating a national database of injection wells. Links to useful injection well data are being compiled at the website pmc.ucsc.edu/~seisweb/Induced/. The second purpose is to draw qualitative conclusions about the spatial and temporal relationship between triggered seismicity and injection wells based upon collected data.

2. Current Data Availability:

Earthquake Data

National earthquake data can be obtained via the Northern California Earthquake Center’s website (NCEDC.org). The NCEDC creates and stores the Advanced National Seismic System (ANSS) earthquake catalog. Built from data contributed by individual seismic networks across the US and the world, the ANSS catalogs worldwide seismic events. Each seismic network that contributes to the ANSS catalog provides data for a geographic region where its data is considered to be the most accurate for that location.

The ANSS’s catalog of earthquakes is not a perfect source of seismic data. As a compilation of several seismic networks, the ANSS is not uniform in its coverage. Some seismic networks are more accurate. For example, urban areas near major active fault zones typically receive more accurate monitoring compared to rural aseismic areas. Another weakness of the ANSS is that historical data quality varies as a function of location. Significant earthquake monitoring did not occur outside of California and Alaska until the 1960’s and 1970’s (NCEDC). As a result, most geographic regions across the US do not have accurate earthquake data past 40 years ago.

Downloadable Well Data
No database of United States injection wells exists. In order to construct such a database, useful data links are being collected at [pmc.ucsc.edu/~seisweb/Induced/] on a state-by-state basis.

States provide injection well data in a variety of formats. An ideal dataset is one that provides injection well locations as well as production/injection figures per well. Such datasets are ideal because they allow the correlation between injection wells and seismicity to be examined spatially and temporally. The absence of location data in well databases is the largest and most common problem when collecting injection well data. Few inferences can be made about the relationship between seismicity and injection wells if the locations of wells are unknown.

The database of Oklahoma injection wells, which can be found at the above mentioned website, provides a template for a near ideal dataset. Injection well records are presented as an excel spreadsheet, which was provided by the Oklahoma Corporation Commission (OCC). The spreadsheet provides relevant well data such as API number (a unique ID number), monthly injection data, and well location coordinates. Oklahoma’s Underground Injection Control (UIC) spreadsheet is the best injection well data found for any state. Other states, besides Oklahoma, also provide UIC datasets. However, no other injection well database is as complete with both locations and injection history as Oklahoma’s.

Many states implement a UIC program, typically in collaboration with the national UIC program run by the EPA. However, most states that have a UIC program fail to share their data with the public in an accessible way. Additionally, the EPA has yet to release any meaningful data for public consumption (although it promises to do so in coming years). When available, UIC data is useful because it encompasses the many types of fluid injection
wells (fluid disposal, hydrofracking, mining etc.) that exist. A more widespread release of state UIC data would greatly improve national injection well data availability. This scenario is the most ideal solution for creating an accurate national database of injection wells.

Ultimately, not all states provide comprehensive injection well datasets. If no injection well dataset is available for a state, injection well data must be compiled by indirect means. One indirect mean involves the use of state oil and gas well databases, which are often more available than pure injection well data. Often state oil and gas well data can be filtered to provide only wells that utilize fluid injection. For example, the state of Arkansas provides an ESRI shapefile with all documented oil and gas wells in the state. Arkansas’s oil and gas well shapefile includes a “well type” attribute in its database. Using the “well type” attribute, Arkansas’s shapefile can be queried to produce only oil and gas wells that have a type classification such as “Salt Water Disposal” or “Injection”. Querying oil and gas well data is a useful workaround when statewide injection well data does not exist. However, this tool is typically less than ideal for two reasons. One: Results do not include non-oil and gas related injection wells, such as hazardous waste disposal wells. Two: Oil and gas well databases typically do not include injection data.

The USGS provides a generalized map of US oil and gas production locations. Records dating back to 1900 are included in the map data, which can be viewed via web browser or downloaded as a Google Earth kml file/Esri shapefile. A significant drawback of the USGS’s map is that records are only current through 2005. Also, a grid of 1km by 1km cells generalizes the map’s well records. Each cell is color-coded depending on the primary type of production occurring within its boundaries (oil or gas). Because of this generalization, oil and gas wells that utilize injection cannot be differentiated from non-injection wells. The
USGS oil and gas data is useful for broad analysis on large scales. The database gives a general sense for where oil and gas production is occurring in the US. If the assumption is made that most modern oil and gas production companies utilize hydrofracking techniques or dispose of their waste via fluid injection, the USGS dataset stands as a good indicator of likely fluid injection locations in a broad sense.

![Downloadable Databases Available for Contiguous US](image)

**Figure 1**: States with downloadable well databases. Color indicates available data type. "Other downloadable data" includes well databases lacking well locations.

**Online Data**

Online permit/well log databases are a data resource that can be utilized to enhance the informational completeness of downloaded injection well or oil and gas well databases. Permit/well log databases provide a directory of state well permits. Permits and well logs contain detailed information about a specific well. Information provided by a well permit may include installation date, ownership details, as well as production/injection figures. Permit and well log databases are an excellent compliment for incomplete downloaded well
databases and can be used to fill in missing information for specific wells of interest. For example, Alabama provides an ESRI shapefile of state oil and gas wells. The geographic point data lacks production figures. However, if a small number of wells are identified by their proximity to earthquakes, production figures for those wells can be found by searching Alabama’s online data. Because online permit results cannot be downloaded in mass, online permit databases are not a substitute for complete injection well databases, such as Oklahoma’s.

Online Geographic Information Systems (GIS) applications, run by state agencies, are another useful data resource. Online GIS applications are web maps that display interactive geographic information, such as injection well locations. State web maps are utilized to quickly gain a general sense of injection well locations. Often, by clicking on a well in a web map application, pertinent well information (such as API number) can be accessed. Online GIS applications are also useful for finding more detailed information about a well when only its geographic location is known. Typically, data from online mapping applications cannot be downloaded. As with online permit databases, online GIS applications act as a complement to downloadable data but cannot completely substitute for such datasets.

Figure 2: States with online injection well resources. Color indicates available data type. "Other supplemental data" includes data such as well lists and regional production figures.
3. Observations

Oklahoma has the most complete database of injection wells for any state. For this reason, observations on the relationship between triggered seismicity and fluid injection will be based upon data for the state of Oklahoma.

Injection wells are more pervasive than earthquakes in Oklahoma. There are 145,000 records in the state’s UIC database. Records are documented by year. Therefore, a single well has a record for each year it injects fluid. Approximately 10,000 unique wells exist as of 2010. The database does not contain well entries after 2010 or before 1987. UIC wells are distributed evenly across Oklahoma’s area. Between the years 1990 and 2011, 465 seismic events with a magnitude greater than 2.5 were recorded in the ANSS catalog. Earthquakes are concentrated towards central Oklahoma.

![Figure 3: Oklahoma Seismicity vs UIC wells](image)

Given that the earthquakes can be separated by hundreds of kilometers, a study area
needed to be established. Additionally, a methodology for determining which wells likely triggered which earthquakes also needed to be developed. To divide Oklahoma’s seismicity into manageable pieces, I used ArcGIS to identify spatially clustered earthquakes through the use of a clustering tool. Earthquakes separated by 1km or less were grouped into clusters outlined by polygons. Three polygons containing over 30 events were identified. Two of these polygons will be used for further observations and will henceforth be referred to as Clusters A and B. Earthquakes at Clusters A and B primarily occurred during 2009 and 2010. The third polygon was ignored because its seismic events primarily took place after 2010, when no injection data is available.

![Earthquake clusters A and B in central Oklahoma. Other clusters exist, but A and B are the largest with over 30 events each.](image)

Davis and Frohlich (1993) outlined seven criteria for identifying triggered seismicity. One criterion was that suspected earthquake epicenters must be within 5km of injection wells.
In order to investigate which injection wells may have been responsible for Clusters A and B’s seismicity, a 5km buffer was drawn around each earthquake within the clusters. Several injection wells fell within these 5km radiuses. Only injection wells active during 2009 and 2010 were considered because triggered seismic events are linked to temporally close injection (McGarr et al., 2002). Further observations will now be continued by specific cluster.

**Cluster A Observations:**

After identifying wells that are proximal to the suspected earthquakes, production data for the selected wells was examined. From 2009 through 2010, injection wells within 5km of a Cluster A earthquakes injected 106,000 barrels of disposal fluid into the subsurface. In November 2009, injection wells within 5km of cluster A injected 6,500 barrels. This was the highest injection volume for any month between 2009 and 2010. Earthquakes peak during a month of globally low injection volume, September 2010.

![Figure 5: Total injection volume per month for injection wells within 5km of Cluster A. Volume is plotted against frequency of seismic events per month. No injection data is available after 2010.](image)
The average injection pressure per well for wells within 5km of Cluster A events was 114 Psi. In January 2010 the average pressure of fluid injection was 162 Psi, the highest for any month in 2009 or 2010. There is a significant drop off in average injection pressure after a global peak in January 2010.

There are 43 earthquakes in cluster A. 38 of these events took place in 2010 and 5 took place in 2011. The rate of earthquakes per month peaks between September 2010 and November 2010 during a period of low average injection pressure.

**Cluster B Observations:**

From 2008 through 2010, injection wells within 5km of a Cluster B earthquakes injected 1,827,841 barrels of disposal fluid into the subsurface. Injection wells within 5km of cluster B injected 62,692 barrels in December 2008, the highest injection volume for any month between 2008 through 2010.
The average injection pressure per well for wells within 5km of Cluster B events was 374 Psi. Average injection pressure peaks around 500 Psi from September 2009 through December 2009. Average injection pressure consistently drops off before and after the late 2009 peak.


Average injection pressure globally peaks before the December, April, and July spikes in seismicity rate. The injection pressure peak precedes the three seismicity spikes by three, seven, and ten months. A spike in the rate of seismicity for August 2008 precedes the injection pressure spike by one month.
4. Conclusions:

The earthquakes mentioned in this paper clearly meet two of Davis and Frohlich’s (1993) criteria for establishing seismic events as triggered. The proximity of earthquakes to injection wells and a lack of previously recorded seismicity in the study area positively answer Davis and Frohlich’s (1993) “Background Seismicity” and “Spatial Correlation” questions. If the events at Clusters A and B are indeed cases of triggered seismicity, there are several implications.

A fault will slip when normal stress acting across the fault plane is overcome by shear stress. The injection of fluid into the subsurface can cause fault failure by reducing normal stress. A reduction in normal stress can be achieved by increasing pore pressure via fluid injection. Both the amount of fluid injected and the pressure of injection play a role in increasing pore pressure (McGarr et al., 2002). As a result, documented triggered seismicity
cases typically exhibit a clear temporal correlation between seismicity and changes to injection pressures/volumes.

Despite typical time dependency for triggered seismicity cases, the seismicity rate at Cluster A appears to lack a clear-cut time dependency on changes in injection variables. For instance, peak average injection pressure lags peak seismicity by 8 months. The rate of seismicity at Cluster A also lacks correlation with changes in injection volume. Peak seismicity occurs during a period of decreasing and overall low injection volumes.

For cluster B, changes in injection pressure appear to coincide somewhat with seismic activity. Seismicity rate spikes three times shortly after an increase in average injection pressure in September 2009. However, a spike in seismicity also precedes the injection pressure peak by one month, weakening the correlation. Meanwhile, changes in injection volume appear to lack any temporal relationship with Cluster B seismicity rate. Peak seismicity occurs during a period of globally low injection volume. Conversely, the global peak in injection volume occurs just as monthly seismicity drops to almost zero.

For neither Cluster A nor B is seismicity clearly linked to changes in injection pressure or injection volume. Cluster A and B would fail Davis and Frolich’s (1993) temporal correlation question, “Is there a clear correlation between injection and seismicity?” If Oklahoma’s seismicity is induced, its relationship with injection is atypical from other literature cases of triggered seismicity, such as Raleigh et al (1976).

The lack of clear temporal correlation between injection and seismicity is further accentuated by looking at larger scale injection activity across Oklahoma. Injection activity is not unique at Cluster A or B. The largest month to month change in average injection pressure, for injection wells proximal to earthquake clusters A and B, was 100psi. There are
32,500 well records from 2008 through 2010 in Oklahoma’s UIC database. 10,000 records have at least one month to month change in injection pressure of at least 100 psi. If a large change in injection pressure was the sole variable responsible for triggering seismicity, there should be far more earthquakes in Oklahoma.

One possible explanation for the apparent lack of temporal correlation between injection and seismicity is a near failure state for faults proximal to the examined injection wells. If existing faults in the study area were on the absolute cusp of failure, shortly prior to the observed seismic events, only a small perturbation in injection pressure or volume would be required to trigger seismicity. This could explain why no significant spike in injection volume or pressure is observed to shortly precede Cluster A and B seismicity. However, this explanation only raises more questions. Fluid injection has been ongoing for years proximal to clusters A and B. Why would faults suddenly be close to failure in 2010 versus 2009 or 2008, when injection was also occurring? Perhaps some larger regional stress change could be to blame? This seems unlikely given Oklahoma’s aseismic nature.

Examining injection data over an unconventionally long timescale may provide a solution for how faults could suddenly be near failure after years of injection (Keranen et al., 2012). Typically, triggered seismic events occur shortly after changes in injection pressure/volume. However, it has been suggested that the seismic events in central Oklahoma may be the result of a build up of pore pressure over the course of decades (Keranen et al., 2012). Impermeable faults surrounding Oklahoma’s well heads potentially created a reservoir compartment that prevented the rapid diffusion of pore pressure away from injection points. The slow build up of pore pressure over a long period of time may have eventually resulted in fault failure. A gradual 20 year increase in measured subterranean pressure near well heads
supports this conclusion (Keranen et al., 2012). Considering this paper’s inability to find a correlation between injection and seismicity over a two year period, a slower build up of pore pressure seems like a plausible culprit for Oklahoma’s recent seismicity. Keranen et al’s (2012) observations about long term increasing injection pressure could not be replicated for the injection wells near clusters A and B (using Oklahoma’s UIC data). However, attempts to repeat Kernan et al’s (2012) findings were only cursory. Further data analysis would be required to be conclusive, an objective outside the scope of this paper. Regardless of the reason, the collected data suggests that seismicity can be induced without large short term fluctuations in injection pressure or volume.

Well locations and injection data alone cannot predict all triggered seismicity cases. All injection wells increase the ambient pore pressure around their injection points to some extent. Yet, not every injection well produces earthquakes. As previously noted, the injection conditions at Clusters A and B are not unique to the study area. Nonetheless, seismicity in Oklahoma is restricted to a small geographic area despite the pervasiveness of injection wells across the state. Ultimately, the non-uniqueness of injection history at clusters A and B indicates other variables must be considered when analyzing induced seismicity. It seems time scale could be an important factor. In situ stress around injection points and local geologic structure are definitely important considerations. In situ stress and geologic structure data are difficult to obtain without conducting field research for specific locations of interest.

The data collected at pmc.ucsc.edu/~seisweb/Induced/ is a small but important first step for creating a national injection well database. However, having a database of injection well locations and injection figures is only one piece of the injection well-seismicity
relationship. More data and research is needed to pin down the relationship between fluid injection and seismicity in Oklahoma and in general.
**References**


Keranen, K.M., Savage, H.M., Abers, G.A., Cochran, E.S. (unpublished) Induced seismicity: significant earthquakes following low-pressure pumping in Oklahoma


