EVALUATION OF HYDROGEOLOGIC DATA ASSOCIATED WITH USGS AREAS OF POTENTIALLY INDUCED SEISMICITY

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I dedicate this research in loving memory of my Grandpa, Bill Ihrig.

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Title of Study: EVALUATION OF HYDROGEOLOGIC DATA ASSOCIATED WITH AREAS OF POTENTIALLY INDUCED SEISMICITY

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Abstract: The Central and Eastern United States have experienced an increase in seismic activity within the last forty years with a corresponding concern from the public regarding the associated seismic hazard. In 2015, the United States Geological Survey identified 17 areas at risk for seismicity induced through industrial processes. Each area contains research investigating the origin of seismicity and found possible correlations to injection disposal wells. These wells are often used by the petroleum industry to dispose of wastewater and other byproducts from the resource extraction process. As this fluid is pumped beneath the surface it increases pressures near critically stressed faults, which can induce seismicity. This study is a systematic review of the 17 identified potentially induced seismic areas to identify patterns among the varied geographical settings. With a focus on hydrogeology, the goals of this research include discovering what hydrogeologic data are available, how far pressure migration is expected to travel, and if a relationship exists to evaluate hydrogeologic risk of seismicity using available hydrogeologic data. Results of this study show a considerable lack of hydrogeologic data related to injection disposal wells and the injection interval. This research confirmed a proximal radius of 2.0 km (1.5 miles) where initial felt seismicity occurs. Fifty percent of seismicity occurs within 10 km (6.0 miles) of injection disposal wells, and 90% of the seismic activity occurred within 48 km (30 miles) of wells within the 17 PISAs. Based on this research, using estimated or textbook values for pressure migration prediction is not advisable due to the varied nature of geological settings. The collection of transmissivity, storativity, and formation pressure values, both at the well site and throughout the injection formation, would be worthwhile to adequately assess seismic hazards. This systematic review of the 17 areas provides a quantitative understanding of felt seismicity patterns for improving injection management practices and assessing seismic hazards.

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CHAPTER I

INTRODUCTION

Since 2009, the U.S. has experienced a significant increase in seismicity in the midcontinent region, also known as the Central and Eastern United States (CEUS). The National Research Council (NRC) identified 48 locations within the U.S. with observed occurrences of human influenced or induced seismicity. The seismicity within these locations is linked to industrial fluid processes, such as hydrocarbon storage, retrieval, or wastewater disposal (NRC, 2013). The United States Geological Survey (USGS) announced in 2014 the locations of 14 areas that may be correlated to these industrial fluid processes (Petersen et al., 2014). Three additional areas were added to the USGS list in 2015, making a total of 17 seismic areas “at risk” for industrially induced seismicity (Petersen et al., 2015). The USGS identified Potentially Induced Seismic Areas (PISAs) stretch across eight states. The names and locations of these specified PISAs are shown in Figure 1.1.

In all 17 PISAs, peer review literature indicates the increase in seismicity is likely associated with subsurface injection disposal wells (Appendix A-C). Sixteen of the 17 locations have peer-reviewed literature attempting to determine the origin of seismic onset (research within the remaining unstudied location is ongoing). The radial movement of injection fluid from the center location of a disposal well, as it crosses naturally occurring faults in the subsurface can cause earthquakes (Ake, Mahrer, O'Connell, & Block, 2005; Healy, Rubey, Griggs, & Raleigh, 1968; Herrmann, Benz, & Ammon, 2011; Herrmann, Park, & Wang, 1981; Horton, 2012; McGarr, Simpson, & Seeber, 2002; Nicholson & Wesson, 1990). Research in some of the USGS identified PISAs has confirmed induced seismic events, such as the earthquakes in Rangely and Rocky Mountain Arsenal in Colorado (Healy et al., 1968; Raleigh, Healy, & Bredehoeft, 1976).

Not all research has been successful with linking injection wells to local seismic activity with high levels of scientific certainty. Keranen, Savage, Abers, and Cochran (2013) explained hydraulic data such as reservoir pressure, formation permeability, and injection fluid volume are needed to conclusively link Oklahoma's seismic activity to subsurface fluid injection. Similarly, results in the Dagger Draw oil field in New Mexico indicated a lack of data regarding wellhead pressures, fluid injection, and earthquake data to be able to conclusively verify induced seismicity (Sanford, Mayeau, Schlue, Aster, & Jaksha, 2006). Researchers investigating increased seismicity in Brewton, Alabama explained the difficulties identifying induced seismicity without knowing the fluid properties, movement of subsurface pressure, and material properties (Gomberg & Wolf, 1999). The lack of hydrogeologic data remains a consistent theme among these induced seismicity investigations. Ellsworth (2013) emphasizes the lack of hydrogeologic data, stating more subsurface formation properties are needed to enhance induced seismicity research. McGarr et al. (2015) further support this claim adding the importance of locating faults and identifying subsurface formation properties is crucial to managing injection induced earthquakes.

Statement of the Problem

The 17 USGS identified PISAs were excluded from the 2014 National Seismic Hazard Map (Peterson et al., 2015) for the final analysis due to anthropogenic influence (Figure 1.1).

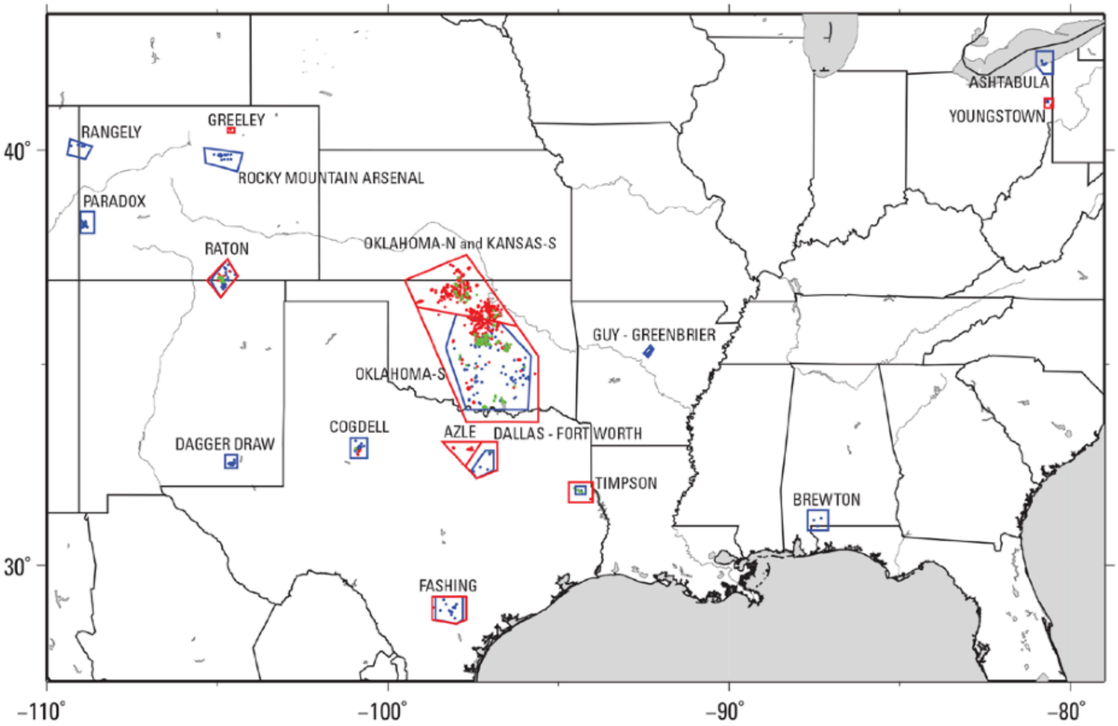

Figure 1.1. The locations of the 17 areas removed from the USGS National Seismic Hazard Map are indicated with red (nondeclustered) and blue (declustered) polygons. Red (2014), green (2013), and blue (2012) dots indicate earthquake epicenters. Image from Peterson et al. (2015).

In 2016, the USGS attempted to quantify the seismic hazard within these areas by evaluating earthquake patterns, rates, and ground motion data. However, the USGS does not attempt to address the cause of seismicity and acknowledges there are many gaps in the scientific research, such as fault locations and orientations, hydrogeologic characteristics, and incomplete records of injection and formation pressures, rates, and volumes (Peterson et al., 2016; Weingarten, Ge, Godt, Bekins, & Rubinstein, 2015). Without additional scientific support, there remains uncertainty in how to address the potential hazard stemming from induced seismicity.

A critical need exists within the literature for hydrogeologic data in order to determine the origin of seismic activity. Without additional hydrogeologic information, the scientific community lacks evidential support for claiming induced seismicity, and cannot make reliable predictions for current seismic hazard or future projections of seismic hazard.

Purpose of the Study

These 17 PISAs span across eight states, which vary in geological setting, industrial exposure, and seismic history. Comparing the research across the 17 locations may reveal patterns for addressing induced seismicity concerns despite the differences among geographical locations. The focus of this systematic investigation among PISAs is the hydrogeology of each location and its use within research efforts. It is likely there is a critical lack in hydrogeologic data, which hinders hazard predictions within PISAs. It can be hypothesized that obtaining these data sets would reveal patterns among PISAs allowing for distance projections for pressure migration and analytical solutions for assessing fluid induced seismic hazard. The purpose of this study is to conduct a systematic review of peer-reviewed research investigations related to the 17 USGS identified PISAs to discover if hydrogeologic trends exist among the various locations. This research focuses on three areas of interest:

1. To identify patterns and the availability of hydrogeologic data within induced seismicity research;
2. To estimate the distance seismic hazard should be monitored from a well once subsurface injection is initiated;
3. To discover whether estimated formation hydrogeologic parameters are useful to generate hydrogeologic predictions of induced seismic hazards.

Significance of the Study

Most induced seismicity studies evaluate structural and seismic properties, but the inherent triggering mechanism is the transmission of subsurface pressure pulses (Davis & Pennington, 1989; Raleigh et al., 1976). This research may establish the importance of hydrogeologic measurements for evaluating hazards within PISAs for the scientific community, regulatory agencies, and general public. If patterns exist among the 17 PISAs, this systematic review will be able to provide regulatory agencies with scientific evidence to support classification of induced seismic areas and future policies for injection disposal wells. Understanding the hydrogeologic characteristics of an injection location may help determine and assess risk of injection, provide opportunities for effective management of seismic hazard zones, and provide a proactive approach to injection processes. Regulators may use hydrogeologic data to locate viable locations for future injection sites, identify what rate or volume is allowable in specific formations, and provide a cautionary radius around injection wells where seismicity may occur.

Considerations for this research include potential patterns to conduct injection aseismically, or methods for early detection to limit seismicity. Through analytical solutions discovered by trend modeling, this research could demonstrate the ability to calculate the pressure migration across various geological. General patterns for calculating injection well pressure migration would be beneficial to state and federal agencies when regulating injection disposal wells.

Research Questions

Removing the 17 PISAs from the recent National Seismic Hazard Map led to the overarching question: How can the hazard associated with PISAs be determined? This question is complex, encompassing various aspects of seismology, structural geology and hydrogeology. The focus of this research concentrates on hydrogeology, as pressure migration is an essential part of induced seismicity research. Three additional questions arose when attempting to address the hydrogeology associated with injection-induced seismicity, which led to three separate research investigations. For each investigation, a leading question emerged and those questions are described as follows:

1. What hydrogeological site data exists among U.S. PISA research locations?
2. Is there a consistent distance we can expect seismically triggering pressure differences to travel based on the location of felt seismicity?
3. If we were to estimate aquifer properties, would these quantities be able to improve seismic hazard predictions?

Research Design

This research was conducted through a systematic review of 33 peer-reviewed research investigations specifically addressing the 17 USGS identified PISAs. Systematic reviews are among the highest level of evidential support when attempting to address a particular issue, as evidenced by the medical profession (Figure 1.2).

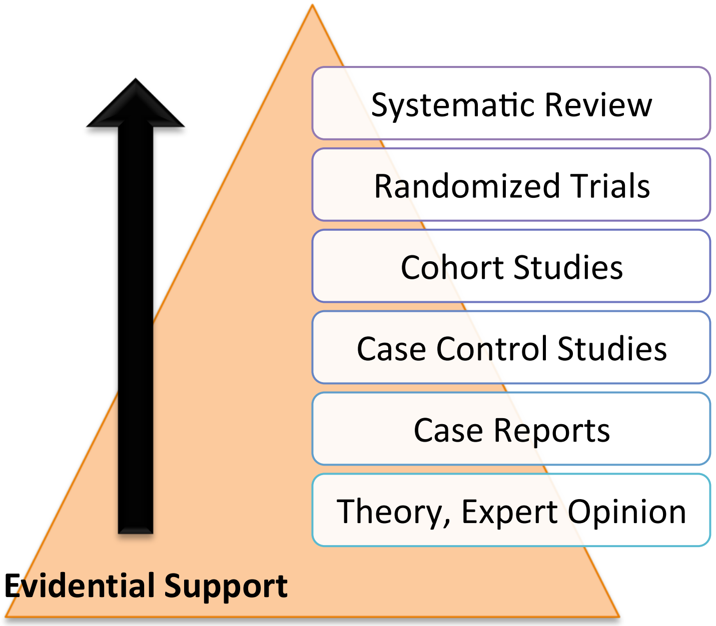

Figure 1.2. Pyramid structure of a systematic review. As new evidence is gained, research groups become broader and scientific certainty increases (Barnes & Halihan, in review).

There are five steps to conducting a systematic review (Khan, Kunz, Kleijnen, and Antes, 2003): (1) framing the questions, (2) identifying relevant research, (3) determining the quality of research, (4) synthesizing the data, and (5) interpreting results. The research questions and sub-questions are described in the previous section. The relevant research includes all articles conducting research on induced seismicity within the 17 USGS identified PISAs. Each article under review was peer-reviewed and published in an academic journal, establishing the validity of the chosen articles. Synthesizing the research presents difficulties, as each research investigation used different strategies and instrumentation to determine the results. Each research article was reviewed and hydrogeologic data points were extracted from each article and compiled into a single dataset (Appendices A – C). Captured hydrogeologic parameters included: injection rate, injection volume, specified well names, name of targeted injection formation, injection depth, injection interval thickness, type of disposal well, initial injection date, final injection date, transmissivity, effective porosity,

porosity, permeability or hydraulic conductivity, diffusivity, and storage. Felt earthquake locations (magnitude > 2.5) were found through the Advanced National Seismic System (ANSS) Comprehensive Catalogue (ComCat) earthquake database available through the USGS to provide consistent seismic data for felt earthquakes among the majority of locations. One PISA, Rocky Mountain Arsenal, had data supplemented from the literature for an older case. Largest earthquake, deepest earthquake, and the radius of earthquake distances were recorded. Injection well locations were provided in some cases, but additional research into state regulatory databases was necessary to identify well locations. To supplement the available hydrogeologic data, values for transmissivity, hydraulic conductivity, and injection interval thickness were researched through geological texts, articles, and databases. Sensitivity analyses often indicate to which conditions systems are most sensitive (Mercer & Faust, 1980). A sensitivity analyses was incorporated into the research design to discover how key parameters influence the results. The methods used were designed to achieve consistency among the locations. These procedures are described in detail in the methodology sections of each research investigation. Likewise, the interpretation of results is included within each investigation description.

Assumptions, Limitations, Delimitations

The NRC identified 48 locations across the U.S. possibly experiencing induced seismicity, yet this research focuses on only 17. These 17 were selected because they were the first locations federally recognized as PISAs. As in any systematic analysis, more locations and data sets could strengthen the overall findings of these investigations. Oftentimes, atypical site-specific details critical to an individual location may get misrepresented when completing a systematic review. The results of this research do not replace the need for capturing site-specific parameters critical to creating a conceptual model of the individual locations.

The ANSS ComCat database used to locate earthquake occurrences maintains a record of events starting from 1973. The locations within the 17 PISAs with earthquake occurrences prior to 1973 were not included in the distance evaluation. The selected magnitude for this research was set at 2.5 or larger. The USGS database does not include smaller magnitude earthquakes (less than 2.5). The USGS database is sufficient for this research, as it focuses on felt earthquakes (greater than 2.2), which also have the potential to produce damage to the surface (Gutenberg & Richter, 1942). Most researchers deployed seismic monitoring stations after earthquakes occurred to capture as many earthquakes as possible, including smaller magnitude earthquake activity. Therefore, articles within the 17 PISAs often reference more earthquake occurrences than provided in this investigation. The seismic stations deployed across the 17 locations varied in functionality, creating inconsistencies among seismic catalogs for these locations. The USGS database provides consistent and reliable felt earthquake occurrence locations across the PISAs.

The Thiem and Theis equations are used for calculating subsurface pressure migration from an injection well (Davis & Pennington, 1989). The Thiem equation is for steady state conditions, while Theis is for transient aquifer conditions (Fetter, 2000). Assumptions for these equations include a homogeneous, isotropic aquifer, with a constant injection rate. Assumptions can be adjusted with site-specific conditions once those components are known. These equations are reasonable for evaluating subsurface pressure migration within PISAs (Davis & Pennington, 1989). Since pressure migration is one of the most critical unknown parameters regarding induced seismicity, the Thiem and Theis equations are justified despite general assumptions. There are other geological unknowns such as fault locations, lengths, and orientations required to address regulatory concerns with injection disposal wells (Weingarten et al., 2015). These aspects are not addressed in this research, as the focus of these investigations lies in hydrogeologic controls on felt seismicity.

Summary

Induced seismicity literature indicates an apparent lack in hydrogeologic data necessary to calculate pressure migration from an injection disposal well to a critically stressed fault (Ellsworth, 2013; Gomberg & Wolf, 1999; Keranen et al., 2013; McGarr et al., 2015; Sanford et al., 2006). The 17 USGS identified PISAs provide a basis to begin examining patterns among locations in order to address the increasing seismic hazard occurring within the CEUS, as they are federally recognized as at risk for induced seismicity (Peterson et al., 2015). A systematic review of these locations is a viable approach, as it provides consistent methods of analyzing data across multiple research investigations. Since each location varies in geologic setting and site-specific conditions, any patterns found among these locations will help scientists and regulatory agencies evaluate methods of managing seismicity and industrial processes responsible for inducing earthquakes.

CHAPTER II

REVIEW OF LITERATURE

A combination of advancements in the hydrocarbon recovery process and an increase in magnitude of industrial fluid injection within the last decade has played a role in the increase in seismic activity within the CEUS (Hammer & VanBriesen, 2012; Rubenstein et al., 2015). To address the concerns of increased seismicity within these areas, it is first important to describe the origin and effects of industrial fluid processes and how they relate to induced seismicity.

Hydraulic Fracturing

Hydraulic fracturing, also referred to as fracking, is a technique used to enhance the production of natural resources, predominately natural gas. Hydraulic fracturing was first introduced as a new technique in the U.S. in the 1940's (Hubbert & Willis, 1972). Hydraulic fracturing is a method used to stimulate or treat production wells in unconventional reservoirs (Huitt, Glenshaw, & McGlothlin, 1964; Hubbert & Willis, 1972; GWPC & IOGCC, 2014). Traditionally, oil and natural gas is trapped in large pockets of rock strata, where the resource accumulates in "pools" within the reservoir. In unconventional reservoirs, the oil and natural gas is trapped within the pore spaces of sedimentary rocks, such as shale and porous limestone. Hydraulic fracturing is a non-traditional method allowing the extraction of natural gas otherwise inaccessible by traditional drilling methods (GWPC & IOGCC, 2014).

The hydraulic fracturing process begins with drilling a borehole into the subsurface and stopping when a natural gas bearing rock formation is reached, which can be anywhere from 2 to 4 km (1 to 2.5 miles) beneath the surface on average (Figure 2.1). After drilling, the borehole is lined with a casing typically consisting of cement and steel piping. Using a perforation device with explosive charges, small holes and fractures are created through the casing and the targeted rock formation (GWPC & IOGCC, 2014). This completes the well establishment process.

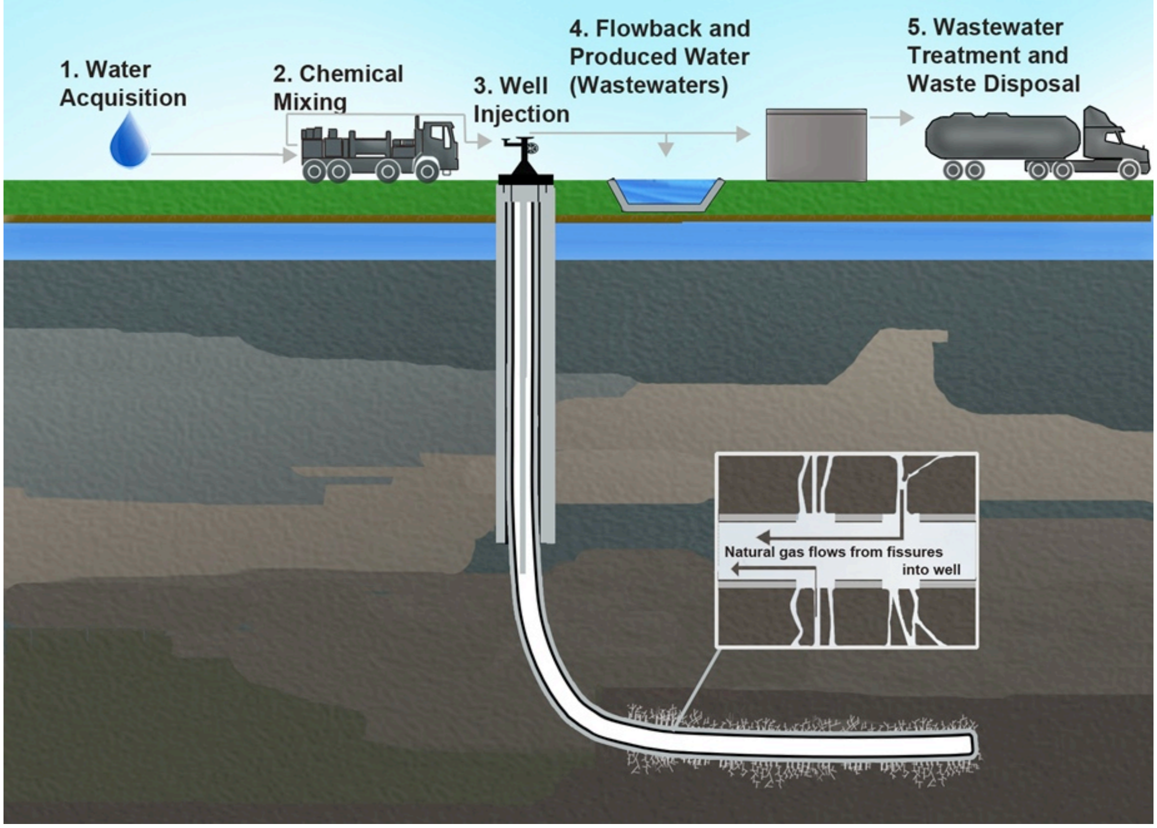

Figure 2.1. Artist depiction of a typical hydraulic fracturing well implementing horizontal drilling. This image also shows natural gas flowing through the manmade fractures. Image source: EPA (2016).

Large volumes of pressurized fluids are pumped into the completed well to generate fractures to yield hydrocarbons in the formation. The fluids used in the process contain a mixture of water, granular solids (typically sand), and chemical additives. The numerical percentage of the fluid that is water, sand, or chemical additive varies depending on the type and depth of the well and the type of rock formation in which the hydraulic fracturing is occurring (Veatch, 1983). The water works as a transport mechanism to get the sand into the newly created fractures. Also, the water is pressurized so it can extend into both the newly created fractures and naturally occurring weaknesses in the formation. The sand is referred to as a proppant, or propping material, which is critical to the hydraulic fracturing process as it props open the newly formed fractures allowing natural gas to flow out of the rock once the fluid is removed (Huitt et al., 1964). The purposes of chemical additives within the water are extensive, including but not limited to: corrosion inhibitors to protect the casing, acids to dissolve minerals, crosslinkers to maintain viscosity as temperature increases, gels to thicken the water and suspend proppant, and surfactant to reduce surface tension and improve fluid recovery (GWPC & IOGCC, 2014). The operators pump a percentage of the water back to the surface before the natural gas is collected, referred to as flow back.

Although hydraulic fracturing began in the 1940's, recent advances in technology have significantly increased the number of well sites using the technique in the last 20 years (Hammer & VanBriesen, 2012). In a process known as horizontal drilling, the borehole is extended horizontally into the targeted formation for an additional 1-2 km (1 mile). Horizontal drilling, using advanced GPS and drilling technologies, allows industries to pinpoint the exact location within the formation most conducive to production, increasing productivity. Industries drilling for natural gas are able to reduce the number of well sites by drilling horizontally within the formation, which lowers the impact at the surface. More than one million hydraulically fractured wells are currently operating in the U.S. (Riddlington & Rumpler, 2013).

Industrial Wastewater

There are many terms used in reference to the waters used in the fracking process. Hydraulic fracturing fluid is water treated with the proppant and chemical additives and injected into the well. Produced wastewater is the fluid mixed with formation minerals after injection, which returns to the surface through the well after the production of natural gas. Produced wastewater contains chemical and metallic contaminants from the formation, which may be harmful to the environment (Hammer & VanBriesen, 2012). Contaminated water is produced through drilling site preparation, drilling itself, operation, and use of the hydraulic fracturing technique (Hammer & VanBriesen, 2012). Commonly, the original water used in the process is fresh water retrieved from lakes, streams, or municipalities (Veil, 2010).

A maximum of 75% of the injected fluid is retrieved in the hydraulic fracturing process (GWPC & IOGCC, 2014). Flewelling and Sharma (2014) found physical constraints prevent the upward migration of hydraulic fracturing fluid; therefore, the remaining 25% of wastewater remains in the fractured formation. After well operators retrieve wastewaters from the well, it must either be treated or disposed.

Energy companies have implemented several strategies to address produced wastewater. According to Hammer and VanBriesen (2012), there are five basic strategies for managing the chemically treated wastewater retrieved in the process: (1) minimizing the produced wastewater, (2) recycling, (3) treatment, (4) beneficial reuse, and (5) disposal. Minimization of wastewater production is implemented at the well site.

Advanced technologies and mechanical blocking devices are minimization methods, but these methods are not as popular with oil and gas companies because the technology is still being developed and the effects are uncertain (Hammer & VanBriesen, 2012). Treated wastewater can be reused outside of the hydraulic fracturing process as water for livestock, vegetable cultures, irrigation, and fire control (Adebambo, 2011). Treatment and recycling methods are more commonly used for managing wastewater. Within recent years, some oil and natural gas companies have begun creating facilities and/or management procedures regarding the treatment or recycling of wastewater. Chesapeake Energy Corporation has designed water filtration processes for eight different formations across the country to help reduce the amount of contaminants (Terry-Cobo, 2013a). Devon Energy has constructed a water recycling facility to treat and reuse wastewater within the hydraulic fracturing process. The recycled fluids will be reused until the level of chlorides reaches 30,000 parts per million. Wastewater with this level of chlorides may clog the well, which makes it hazardous to the process and it must be disposed (Terry-Cobo, 2013b). When industrial wastewater is too contaminated or too costly to treat and reuse, it must be disposed. According to the U.S. Environmental Protection Agency's (EPA) Underground Injection Control (UIC) section of the Safe Drinking Water Act (SDWA) of 1974, using a Class II injection disposal well is the safest option for disposing wastewater or storing hydrocarbons produced from the oil and natural gas production process in order to protect the environment and public drinking water (EPA, 2012).

Injection Disposal Wells

The purpose of an injection disposal well is to prevent the upward migration of contaminants into groundwater or surface water; therefore, the injection well targets a porous, non-permeable rock formation for which the fluids are confined (EPA, 2012). Several classes of disposal wells exist, but a Class II well exclusively targets wastewater and hydrocarbons resulting from oil and natural gas production (EPA, 2012). State organizations such as the Texas Railroad Commission in Texas and the Oklahoma Corporation Commission in Oklahoma regulate and monitor each Class II injection well within their region. Injection disposal wells are created in a process similar to traditional oil and natural gas wells, except the goal is to drill into a porous, non-permeable rock formation where the injected wastewater will be contained (EPA, 2012). In some cases, the wastewater can by injected back into an existing production well after the resources are exhausted.

There are over 11,000 active and inactive injection wells currently in Oklahoma, which contains the two largest PISAs in surface area (OCC, 2016b). Over 55,000 injection wells are located in the state of Texas, which includes five of the 17 PISAs (RRC, 2015). As of 2012, there were over 150,800 Class II injection disposal wells in the U.S. (Lustgarten & Schmidt, 2012). Not all regions of the U.S. are conducive to injection disposal wells. For example, there are only eight disposal wells in the entire state of Pennsylvania (McCurdy, 2011), even though hydraulically fractured wells are common in this state. This is because Pennsylvania does not have confined injection intervals capable of preventing the vertical migration of wastewater fluids. When using a Class II injection disposal well, the injected wastewater extends in all directions throughout the porous, non-permeable rock formation with no artificial barriers containing the fluids. Although natural gas retrieval companies must follow state and federal standards for disposing wastewater, there is always the threat of contamination or other harmful environmental impacts when dealing with chemically treated water, whether by accident or ignorance.

Environmental Impacts of Hydraulic Fracturing and Wastewater Disposal

Economic impact. Natural gas retrieved from the hydraulic fracturing process (i.e. shale gas) is one of the fastest growing energy sources in the U.S., accounting for over 60% of the U.S. gas supply (U.S. Geological Survey, 2014a). Americans consumed 22,467 billion cubic feet of natural gas in 2011 (U.S. Energy Administration, 2016). Natural gas consumption increases each year, with a total of 27,474 billion cubic feet consumed in 2015 (U.S. Energy Administration, 2016). Because Americans are increasing their consumption of natural gas, there is a demand to maintain a national supply. According to an IMPLAN model developed by Miller and Blair (2009) for the state of Pennsylvania, the shale gas industry in 2008 was responsible for “2.2 billion [dollars] in economic activity, the creation of 29,284 jobs, and the payment of 238.5 million [dollars] in state and local taxes within the commonwealth of Pennsylvania” (Kinnaman, 2011, p. 1244). Oklahoma’s oil and gas industry supports 364,300 jobs, employs a quarter of the state’s population, and the oil and gas industry contributes $50 billion of Oklahoma’s $150 billion economy (OKOGA, 2016). The oil and gas industry in Texas generates over 315,000 jobs and established a “Rainy Day Fund” of over $2.2 billion, which helps statewide shortfalls in education, health insurance, child protective services, and disaster recovery programs just to name a few (PBPA, 2014). In 2011, the nationwide employment in the oil and gas industry consisted of over five percent of the total employment. The oil and gas industry generated over $550 billion dollars, which was eight percent of the U.S. total economy (API, 2013). Despite the economic value, resistance to hydraulic fracturing and wastewater disposal exists in the U.S. due to health and safety concerns.

Societal impact. If natural gas is unattainable by traditional methods in the quantities required, hydraulic fracturing is critical to maintaining stores of natural gas for U.S. consumption. However, there is public opposition and confusion regarding hydraulic fracturing. A survey of Americans in 2012 found only 26% of Americans were well-informed about the hydraulic fracturing process, 35% had heard nothing at all, and for those who had heard of it, 35% were opposed to its use (Pew Research Center for the People and the Press, 2012). Boudet, Clarke, Bugden, Maibach, Roser-Renouf, and Leiserowitz (2014) found 39% of Americans had heard nothing at all regarding the hydraulic fracturing process and only 9% of Americans were well-informed. Additionally, 22% of Americans were strongly opposed to hydraulic fracturing and 20% of the population supported it, regardless of how well informed they were about the process (Boudet et al., 2014). Boudet et al. (2014) found those who opposed tended to be more informed about the process and referenced environmental impacts of hydraulic fracturing. Several organizations maintain websites advocating against the process of "fracking" for oil and natural gas extraction: *americansagainstfracking.org*, *nyagainstfracking.org*, *artistsagainstfracking.org*, *dangersoffracking.com*, *californiansagainstfracking.org*, *dontfrackwithus.org*, *nationalgrassrootscoalition.org,* and many more. According to these anti-fracking websites, social anxiety over fracking stems from the environmental issues surrounding the hydraulic fracturing process, or more generally hydrocarbon production techniques.

Little to no peer-reviewed research exists examining perceptions of induced seismicity. Misconceptions and inaccuracies regarding induced seismicity are reported through media outlets, which exacerbate public confusion (Rubinstein & Mahani, 2015). Common misconceptions include all earthquakes are caused by hydraulic fracturing (only a small percentage; Rubinstein & Mahani, 2015), there would be no wastewater disposal without hydraulic fracturing techniques (nearly all production wells produce wastewater; Rubinstein & Mahani, 2015), and all injection wells create earthquakes (most do not; Rubinstein & Mahani, 2015). Despite addressing common misconceptions among the public, there remains genuine concerns regarding impacts to the environment.

Environmental impact. A major environmental concern with hydraulic fracturing is the large volume of water required for the process. For example, approximately 3,800,000 gallons of water per well is needed to complete the hydraulic fracturing process while drilling in the Marcellus Shale, which is a large oil and natural gas play in northeastern U.S. (Veil, 2010). The use of millions of gallons of fresh water for hydraulic fracturing could be a concern in areas with water scarcity (Veil, 2010). For reference, the amount of fresh water used in the hydraulic fracturing process includes approximately four percent of the total estimated uses of U.S. fresh water (Maupin et al., 2010). Other uses of fresh water include public supply at 12%, irrigation for agriculture at 33%, and thermoelectric power at 45% (Figure 2.1; Maupin et al., 2010).

The multiple ways of creating wastewater also provides multiple opportunities for contamination of the surrounding environment. Hydraulic fracturing requires hundreds of semi-truck loads to transfer the millions of gallons of water to each well site and then to treatment facilities or injection well locations, which can increase carbon emissions. Well operators and truck drivers may accidentally spill the wastewater onto the land surface at the well site, in transit to disposal wells, or in transit other destinations such as water treatment facilities (Hammer & VanBriesen, 2012).

Groundwater contamination can occur when the induced fractures from fracking are hydraulically connected to a fresh water aquifer, or through improperly plugged wells (Groat & Grimshaw, 2012). Air pollution is another environmental concern, as hydraulic fracturing releases dust, diesel fumes, methane, and other particulate matter into the atmosphere (Groat & Grimshaw, 2012). Other contamination possibilities arise through the hydraulic fracturing process: secondary pollution due to transferring wastewater from production site to storage facility; loss of land use due to extreme salt contamination; impacts of water withdrawals; and improper sealing of abandoned wells (Hammer & VanBriesen, 2012).

According to the EPA (2014), the oil and natural gas industry is exempt from the Safe Drinking Water Act (SDWA) of 1974. Diesel and the disposal of wastewater through injection disposal wells are the only aspects of hydraulic fracturing held accountable by the SDWA and the EPA (EPA, 2014). This means tracing contaminants found in local water sources back to hydraulic fracturing sites would be difficult, since the industry does not have to disclose any chemicals (except for diesel) used in the injected fluids. However, the Resource Conservation and Recovery Act (RCRA) does give individual states the authority to require disclosure of harmful chemicals. There are currently 23 states disclosing their industrial chemicals on FracFocus.org. Oklahoma recently passed fracking disclosure rules forcing natural gas industries to post all of the chemicals used in their hydraulic fracturing fluids (McFeeley, 2012). The Oklahoma Department of Environmental Quality and Oklahoma Corporation Commission list the regulations regarding monitoring hydraulic fracturing sites and well water on their websites. Air and water quality monitoring at well sites consists of grab sampling 2-3 days apart or averaging within a 24-hour period, which tests for a broad spectrum of common environmental concerns (OCC, 2016a; DEQ, 2016). Some of the chemicals used in the brine are not found naturally. This means water quality regulators can now trace harmful chemicals found in drinking water sources back to hydraulic fracturing sites.

The hydraulic fracturing environmental concern within the U.S. discussed as the key topic for this research is induced seismicity. Holland (2013) correlated the intense pressure of fluid injected into a subsurface fault during the process of hydraulic fracturing to shallow earthquakes with magnitudes of 0.6 to 2.9, which are sometimes felt at the surface but not strong enough to cause damage. Although Holland linked earthquakes directly to hydraulic fracturing, the low risk factor encourages scientists to focus on induced earthquake sources capable of causing damage. As stated earlier, increased seismicity within the CEUS has been linked to injection disposal wells. This connection between wastewater disposal and induced seismicity from fluid injection led researchers to investigate closely the relationship between these two components.

The disposal of wastewater through injection disposal wells has likely induced seismicity in all of the 17 PISAs, with each location containing various degrees of scientific certainty based on evidential support. Earthquakes have increased in Alabama, Arkansas, Colorado, Kansas, Ohio, New Mexico, Oklahoma, Texas, and Virginia, where the epicenters have all been at or near injection disposal well sites (Ellsworth, 2013). Damage to structural property and residents have been reported in Oklahoma and Texas (Keranen et al., 2013; Frohlich et al., 2014). To begin investigating induced seismicity, it is important to discuss the mechanism of earthquakes and how earthquakes are located and measured.

Earthquakes

Natural earthquakes typically occur along faults in regions classified as tectonically active. An earthquake is a sudden release of slowly accumulated stress at a fault (Bates & Jackson, 1987). Seismologists measure earthquakes with three basic scales: Richter, moment magnitude, and Mercalli Intensity (U.S. Geological Survey, 2014b). The Richter scale measures earthquake magnitude, which is a combination of the amplitude of earthquake waves and duration of event. The Mercalli scale uses human observations and surface destruction to categorize intensity. The Mercalli scale only considers the human impact and the Richter scale does not measure strong earthquakes accurately (U.S. Geological Survey, 2014b). The USGS often uses the Modified Mercalli Intensity Scale to depict the effect of earthquakes to the general public. However, the most common measurement method used by seismologists for earthquakes is the moment magnitude scale. The moment magnitude scale is a refinement of the Richter Scale, which measures earthquake magnitude and intensity. Calibrated seismometers placed in several locations throughout a region can triangulate moment magnitude. The moment magnitude is on a logarithmic scale, increasing by $10^{1.5}$ each time the number of magnitude is increased by one. Most seismologists, geologists, and other scientists studying seismicity use the moment magnitude as the most trusted scale for larger earthquakes(U.S. Geological Survey, 2014b). Throughout this research, magnitude values are assumed as moment magnitude unless otherwise denoted.

Although earthquakes with moment magnitudes of 3.0 or higher typically occur along tectonic plate boundaries, earthquakes are possible along faults in the continental interior due to high shear stress (Peterson et al., 2014; Townend & Zoback, 2000). Areas with high shear stress are at or near the strength limit for the crust. This strength limit means any distress, large or small, applied to a critically stressed fault can trigger an earthquake (McGarr et al., 2002; Nicholson & Wesson, 1990; Peterson et al., 2014). In the U.S., naturally occurring earthquakes with moment magnitudes of 5.0 or greater are rare east of the Rocky Mountains. However, from 2008 – 2011 the annual number of earthquakes in the Oklahoma region was 11 times greater than the annual average number of earthquakes from 1976 – 2007 (Keranen et al., 2013). Rubenstein, Ellsworth, McGarr and Benz (2014) claim a 40-fold increase in earthquakes in the CEUS since 2001.

Distinguishing between natural events and induced seismicity is difficult. There are some differences between the two, which recently have been revealed due to the ongoing research in induced seismicity. Induced seismic earthquakes may tend to have lesser magnitudes than naturally occurring earthquakes (McGarr, 2014). Induced earthquakes often occur in swarms and at shallower depths than natural earthquakes (Gomberg & Wolf, 1999; Seeber, Armbruster, & Kim, 2004). Ground shaking patterns are often more intense with induced seismicity due to the shallow hypocenter locations, but additional research is required to confirm these conclusions (Peterson et al., 2016). Ellsworth (2013) visualizes the changes in the number of earthquakes within the CEUS with magnitude of three or higher, by comparing the projected seismic rate versus the actual seismic rate from 1967-2012 (Figure 2.2).

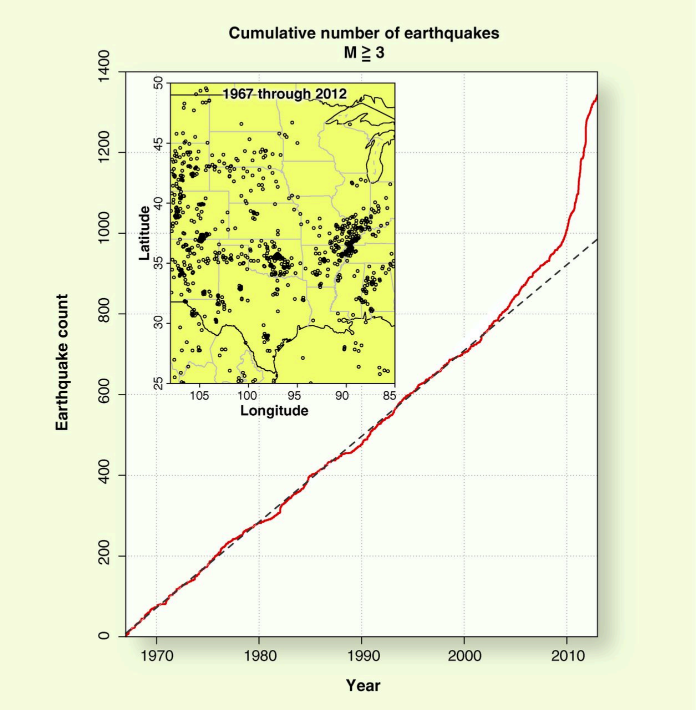

Figure 2.2. Dashed line represents the projected trend of earthquakes of magnitude 3 or greater in the CEUS from 1967 - 2012. Red solid line represents actual earthquakes occurring in the CEUS. Yellow map shows the locations of earthquakes within the CEUS. Image from Ellsworth (2013).

Induced Seismicity

There are four known anthropogenic processes capable of inducing a felt earthquake: reservoir loading, mining, geothermal activity, and fluid injection (Ellsworth, 2013; Simpson, 1986). Reservoir loading is the addition or removal of a large volume of water, which changes the ground stress levels quickly and drastically (Figure 2.3). The underground excavation in mines leads to the removal of large masses of rocks from beneath the surface, thus weakening the formation integrity. Geothermal energy extraction induces earthquakes by removing large volumes of fluids from beneath the surface. To correlate geothermal energy extraction and seismic events, one must quantify the net volume of produced fluid, as opposed to only quantifying the volume of injected fluid (Ellsworth, 2013). Fluid injection into subsurface rock increases the pore pressure within the formation, thus decreasing effective stress and increasing the formation pressure. The increase in overall formation pressure affects physical structures (i.e. fractures and faults) within the injected region (Simpson, 1986).

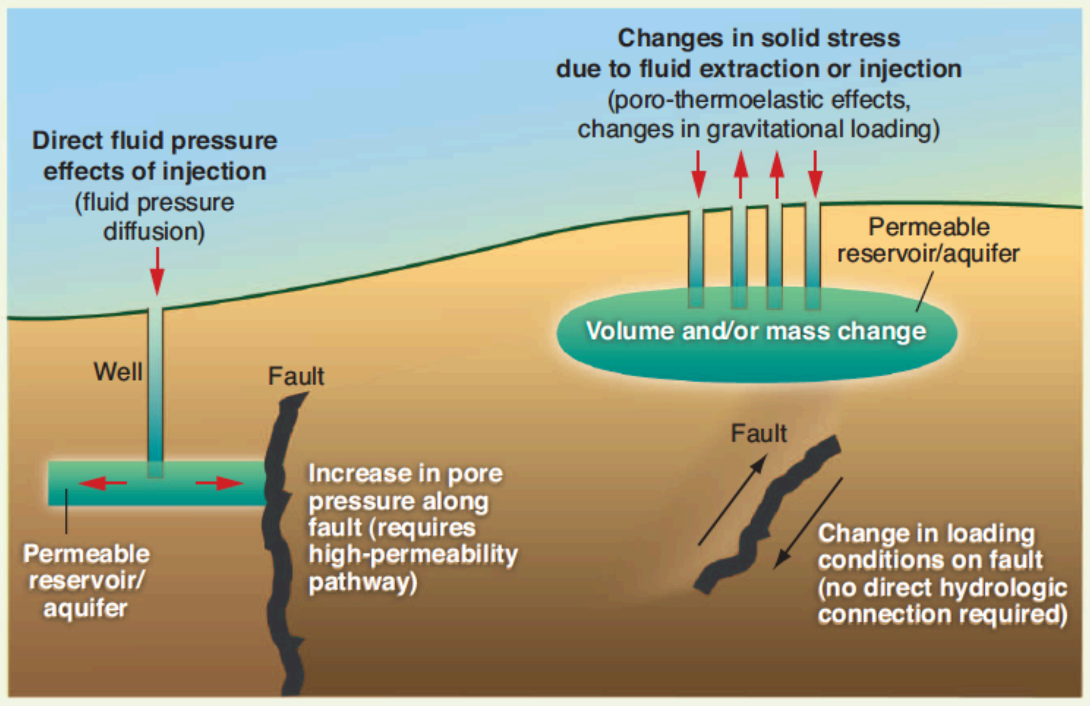

Figure 2.3. Artist depiction of two of the four induced seismic origins: reservoir loading (right) and fluid injection (left). Note in the fluid injection depiction the fluid does not have to reach the fault to trigger an earthquake (Mulargia & Bizzarri, 2014). Image from Ellsworth (2013).

Certain conditions may make faults more susceptible for an induced seismic event, such as high shear stress or increasing pore pressure (Nicholson & Wesson, 1990). The Mohr-Coulomb failure equation is used to determine the critical stress most likely to trigger a seismic event. Mohr-Coulomb failure is expressed by the following equation:

$$\tau_{crit} = \tau_0 + \mu\sigma_n \qquad (1)$$

"where τ_{crit} is the critical shear stress required to cause slip on a fault, τ_0 is the frictional stress on the plane of slip, μ is the coefficient of friction, and σ_n is the normal stress acting across the fault" (Nicholson & Wesson, 1990, p. 7). An increase in fluid pressure on a fault can trigger Mohr-Coulomb failure by reducing the critical threshold within the surrounding rock structures. Nicholson and Wesson (1990) were among the first researchers to supply suggestions for deep fluid injections outlining considerations such as site location, distance from faults, the stress estimate, and the natural seismicity of the region before the establishment of an injection disposal well. Current researchers reference Nicholson and Wesson (1990) frequently to validate induced seismicity findings. For example, Ake et al. (2005) correlated the seismic events at Paradox Valley, Colorado to the fluid injection rates at a nearby injection disposal well through criteria supplied by Nicholson and Wesson (1990).

Davis and Frohlich (1993) published criteria for rationally assessing whether an event is a natural event or induced seismicity. The article provided a starting point for determining whether an event is natural or induced. The authors describe seven questions to ask after a specific seismic event occurs. These questions help evaluate the likelihood of induced seismicity. The authors provide examples of earthquake events, which they submitted through their questionnaire to see if the questions were valid. For example, the authors ran both the Rangely and Rocky Mountain Arsenal cases (both locations were established as seismically induced) through the questionnaire and the results indicated induced seismicity (Davis & Frohlich, 1993). The most important question in the questionnaire is: Do earthquakes occur naturally in the region? Other questions within this research include parameters such as location of the earthquake epicenters, fluid pressures, and correlation of seismic event to fluid injection (Davis & Frohlich, 1993). The authors explained how these questions, if results indicate induced seismicity, were not an absolute indicator of induced seismicity. Although many of the established induced seismic events in literature align with the questionnaire results, further research at each site is necessary to provide evidentiary support. These questions can guide seismologists and other researchers to pursue induced seismicity research or find alternative sources for the onset of an earthquake.

Ellsworth (2013) encourages constant seismic monitoring around injection disposal wells to better understand the hazards of induced seismicity. Current monitoring regulations for Class II injection disposal wells only cover fracture pressure, total injection volume, and average injection pressure (Ellsworth, 2013). Ellsworth (2013) compares the magnitude of natural earthquakes to induced earthquakes. Hazards for major seismic events include, liquefaction, landslides, surface rupturing, and tsunamis if located in or near an ocean. Bird and Bommer (2004) explain these hazards may occur with any ground-shaking event, specifically a magnitude of three or greater. Ellsworth (2013) concludes induced seismic events can have magnitudes as high as six. Keranen et al. (2013) claim this number should be increased due to the 5.7, which hit Prague, Oklahoma in 2011. Although the likelihood of human death or injury in this range is low in the U.S., there are areas in the U.S. where some buildings may not be constructed with earthquake durability and could cause significant damage if subjected to an earthquake with a moment magnitude of six.

Classifying earthquakes and discovering the triggering mechanism for each event is part of the seismological aspect of induced seismicity. Structural geology helps identify critically stressed faults and their orientations, which is important for locating and determining potential hazards of induced seismicity. Locating hypocenters, determining the stress load of nearby critical faults, and mapping distances to injection disposal well locations are all common practices in induced seismicity literature. Hydrogeology of the injection interval has not been as prevalently addressed in the current literature as the structural and seismological components of induced seismicity. Researchers recognize their claims need further hydrogeological data to support their findings beyond a reasonable doubt (Gomberg & Wolf, 1999; Keranen et al., 2013).

Hydrogeologic Parameters

Increasing pore pressure near a critically stressed fault can produce earthquakes (Davis & Pennington, 1989), and fluid injection increases subsurface pore pressure (Raleigh et al., 1976). Earthquakes can be induced by the increase in pressure alone, meaning the fluid itself does not have to reach the fault (Mulargia & Bizzarri, 2014). In order to calculate the distance pressure will travel over time, the hydrogeologic characteristics of the injection interval are needed.

When investigating an area of potentially induced seismicity, it is critical to correlate the injection rate to the location of earthquake hypocenters (Weingarten et al., 2015). Injection rate is important because it indicates how fast the fluid is being pushed into the injection interval. How quickly the fluids move through the injection interval is dependent on the hydrogeology, which is comprised of rock properties (grain size, orientation, porosity and permeability) and fluid characteristics (density and viscosity; Fetter, 1994). Hydraulic conductivity is the ability of rocks to transmit water, also known as the coefficient of permeability, and is derived with the following equation:

$$K = \frac{k\rho g}{\mu} \tag{2}$$

where k is intrinsic permeability, ρ is the fluid density, g is the gravitational constant, and μ is fluid viscosity (Fetter, 1994). Fluid viscosity changes with temperature: viscosity increases as temperature decreases. Fluid density is altered with pressure, temperature, or added minerals. For example, saltwater has a different fluid density than freshwater. The intrinsic permeability of a rock is dependent on primary openings formed as the rock was formed and secondary openings formed after rock formation. Typically shales have low hydraulic conductivity (10^{-9} – 10^{-13} m/s) and are often used to line solid waste disposal sites due to the difficulty of fluids to move through (Fetter, 1994). Chemically precipitated rocks, such as limestone or dolomite, can have high hydraulic conductivity (10^{-3} – 10^{-5} m/s). These types of rocks are often the target lithology for injection disposal wells, as long as they have a confining layer, such as a shale bed, above and below. Additionally, limestones and dolomites are susceptible to secondary openings caused by dissolution. Crystalline rocks, such as igneous basement rock, typically have very low hydraulic conductivity (10^{-9} – 10^{-13} m/s). Secondary openings within these rocks can increase fluid flow by orders of magnitude (Fetter, 1994). The majority of injection disposal wells within the PISAs investigated in this research inject into crystalline basement or karstic limestones and dolomites lying directly above basement rock (Ake et al., 2005; Frohlich, Potter, Hayward, & Stump, 2010; Healy et al, 1968; Hornbach et al., 2015; Horton, 2012; Keranen et al., 2013; Kim, 2013; Sanford et al., 2006; Seeber et al., 2004; Yeck, Sheehan, Weingarten, Nakai, & Ge, 2014). This is why it is crucial to know the extent of fractures and fluid pathways in these systems to discover how quickly fluid is transported.

The most rational approach for discovering hydraulic pathways to a critically stressed fault is to calculate the rate of pressure migration based on injection rate and hydrogeologic characteristics of the injection interval. Davis and Pennington (1989) used the Theis equation to determine fluid migration rates (u). The Theis equation is described as:

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

where *r* is the distance from the well, *S* is storativity, *T* is transmissivity (the product of interval thickness and hydraulic conductivity), and *t* is the time since pumping began. With slight adjustments to accommodate site-specific conditions, the Theis equation has been used to calculate the propagation of pressure waves in the subsurface (Cihan, Zhou, & Birkholzer, 2011; Ferris, 1952; Lee & Wolf, 1998; Saucier, Frappier, & Chapuis, 2010). The Theis equation is used for transient, or unsteady state conditions. For steady state conditions the Thiem equation is appropriate. The Thiem equation is described as:

$$h_0 - h = \frac{Q}{2\pi T} \ln\left(\frac{R}{r}\right) \tag{4}$$

Where h_0 and h are head levels, T is Transmissivity, Q is injection rate, R is the external radius of influence, and r is the radius from the injection well to a radius of interest (Thiem, 1906). Both equations assume a homogeneous, isotropic interval with an infinite lateral extent being injected at a constant rate. These equations can be used in a variety of circumstances and across a wide range of geologic settings. By using the Theis or Thiem equations as a basis to estimate the pressure migration radiating from injection wells, it is critical to obtain the following parameters: injection interval thickness, hydraulic conductivity, storativity, and injection rates. Additionally, pressure measurements should be obtained throughout the injected reservoir. Davis and Pennington (1989) explain although bottomhole pressures at the injection site are important, these measurements are not typically helpful when used in isolation. The pressure analysis for the injection interval could be inaccurate. Useful pressure measurements include data further from the well and throughout the injected formation to gain a better understanding of pressure migration.

Review of Potentially Induced Seismic Areas

A thorough investigation into a PISA would include data sets from structural geology, seismology, and hydrogeology. These three disciplines are not always equally represented within induced seismicity investigations. The following section provides an overview of the 17 PISAs, including descriptions of the location and significant findings.

Rocky Mountain Arsenal, Colorado. Healy et al. (1968) published one of the first investigations of induced seismicity directly linking fluid injection to earthquake events. In 1961, the Rocky Mountain Arsenal installed an injection disposal well for chemical waste, and fluid injection began in 1962. There were two seismometers located in the Denver, Colorado metropolitan area measuring earthquakes in 1962. The authors, in collaboration with the USGS, installed several more to record the increased seismic activity. The increase in earthquakes began seven weeks after fluid injection began. All of the earthquakes classified within the Denver earthquake sequence originated within a radius of 65 km (40 miles) of the injection disposal well. The authors explained the probability of a natural earthquake sequence originating in the same area as the injection disposal well and occurring simultaneously with the onset of fluid injection was 1/2,500,000. In other words, it is highly unlikely the earthquake sequence in Denver from

1962 – 1967 was a naturally occurring seismic event. Earthquakes continued in the Denver metropolitan area even after the termination of the disposal well in 1966. The largest earthquake of the series occurred over a year after the well's termination in 1967, with a magnitude of 5.0. The researchers explained the wastewater beneath the surface continued to radiate outward from the well and increase stress on the surrounding faults, long after the injection ceased (Healy et al., 1968).

Rangley, Colorado. The Denver, Colorado earthquake sequence (correlating injection fluid to earthquakes) sparked interest in researchers to conduct further testing. If fluid injection causes earthquakes, and humans control fluid injection, can earthquake sequences be controlled? Raleigh et al. (1976) tested this question. The researchers needed and injection disposal well where they could maintain control of stress factors and fluid pressure within the area, have the ability to locate the origin of earthquakes, and minimize the risk of inducing a damaging earthquake. The injection disposal well near Rocky Mountain Arsenal could not be used because it was shut down. The researchers collaborated with the Chevron Oil Company to conduct research with four injection disposal wells in the Rangely Oil Field, which had no record of seismicity prior to the experiment. In 1969, the researchers began pumping fluid into the designated injection disposal wells at Rangely and measured the seismicity. One year later, the researchers stopped pumping and began a period of backflow (fluid retrieval) for six months. The researchers recorded over 900 earthquake events from 1969 – 1970, with over one-third of the earthquakes originating 1.0 km (0.6 miles) away from one of the four designated injection disposal wells. During the six-month backflow period, the pressures measured in the formation dropped significantly and the earthquakes averaged approximately one earthquake per month. In 1972, the oil company turned the wells back on and pressure within the formation began to increase. From 1972 – 1973, there was an average of 26 earthquakes per month. The company shut the wells down in 1973, and earthquakes in the region have now ceased (Raleigh et al., 1976). From this research, the authors discovered a critical piece of information: seismic activity dramatically increased after disposal wells reached an injection pressure of 3,727 psi (25.7 MPa; Raleigh et al., 1976). All subsequent research targets this injection pressure (also referred to as bottomhole pressure) as a factor for induced seismicity.

Paradox Valley, Colorado. The injection disposal well in Paradox Valley was used to dispose excess salt water from the Colorado River. Recognizing that Colorado had experienced earthquakes previously due to subsurface injection, this well was a government project to see if they could economically and environmentally dispose of the excess salt water while minimizing the earthquake hazard. Seismicity began four days after initial injection occurred in 1991 (Ake et al., 2005). A seismic swarm occurred in 2013, which was within 6 to 8 km (4 to 5 miles) of the injection well and 4.1 km (2.5 miles) in depth (Block et al., 2014). With little to no background seismicity, the increase in seismicity at Paradox Valley was determined as induced (Ake et al., 2005; Block. Wood, Yeck, & King, 2014). The authors used the locations of earthquakes to discover the pressure migration from injection wells. They concluded calculating the pressure pulse provides a reliable estimate of how fast and far the pressure will travel, to help prevent the pressure from reaching a critical fault. Additionally, the pressure propagation could identify the maximum rate to inject within a location (Ake et al., 2005).

Greeley, Colorado. As of May 2016, there is no peer-reviewed research in the area of Greeley, Colorado regarding induced seismicity. Yeck et al. (2014) presented preliminary findings at the American Geophysical Union in 2014 and described a recent increase in seismicity within this location. With the occurrence of a 3.2 magnitude earthquake in proximity to injection disposal wells, the researchers deployed additional seismic stations to begin consistent monitoring of Greeley. Additional aftershocks including a 2.6 magnitude earthquake occurred three weeks after the seismic stations were deployed. The Colorado Oil and Gas Corporation Commission (COGCC) recommended an immediate cease of injection for the first time in its history (Yeck et al., 2014). Additional research is necessary in this area to support scientific certainty of induced seismicity.

Raton Basin, Southern Colorado and Northern New Mexico. The Raton Basin lies across the borders of Colorado and New Mexico. The Oil and Conservation Division of the Energy Minerals and Natural Resources Department of New Mexico is responsible for regulating the injection disposal wells in New Mexico. No injection data prior to 2006 are available through this entity. Therefore, researchers in this area relied heavily on available data provided through the COGCC. There are several injection disposal wells within the Raton Basin, with over 20 on the Colorado section alone. Rubinstein et al. (2014) completed a statistical analysis regarding the increase of seismicity in the Raton Basin since 2001. They calculated a 3% probability earthquakes would happen naturally in this area. They were able to make spatial and temporal correlations between earthquakes and wells with high injection rates and volumes. The authors attempted to associate high rate and volume injection wells to the increase in seismicity.

Unfortunately, they could not determine whether rate or volume was more important in determining if or when earthquakes will occur (Rubinstein et al., 2014a).

Dagger Draw, New Mexico. As previously stated, there are no injection records prior to 2006 in the state of New Mexico. Sanford et al. (2006) claimed there were no wellhead pressures, fluid injection data, and lacked earthquake numbers and strengths to make suitable correlations to injection activities. Dagger Draw has experienced previous seismicity due to a large magma body at approximately 19 km (12 miles) depth near this location. With a lack of data and a history of seismicity, the authors could not establish a clear connection to induced seismicity. There was a temporal correlation between onset of injection and onset of earthquakes. From 1999 through 2004, the seismicity activity in New Mexico almost doubled (Sanford et al., 2006). Potential correlations could be made in the Dagger Draw PISA with additional data.

Brewton, Alabama. Brewton, Alabama experienced a 4.9 magnitude earthquake in 1997. Gomberg and Wolf (1999) described two injection wells within 5.0 km (3 miles) of the main shock having a focal depth of approximately 4.5 km (2.8 miles). The injection wells reached a depth of 2.1 km (1.3 miles) into a sandstone and shale formation. The volume of extraction and injection of fluids was used to determine if correlations exist between industrial processes and seismicity. The authors could not find a spatial temporal relationship between volumes, pressures and earthquake occurrence. However, injection rates were not evaluated in this study. The authors recognize this relationship is difficult to quantify without fluid properties, an idea of pressure migration, and injection interval material properties.

Ashtabula, Ohio. In the 1980s, earthquakes began shaking the town of Ashtabula, Ohio. Ashtabula is not a seismically active area. Similar to the induced seismic events in the Rocky Mountain Arsenal near Denver, researchers directly correlated earthquakes in Ashtabula to an injection disposal well. Seeber et al. (2004) discovered the earthquakes originated from one of two major faults, which lie within 5.0 km (3 miles) of an injection disposal well. The researchers concluded the wastewater injected into the well acted as a lubricant to facilitate fault movement and trigger earthquakes. The largest earthquake in the Ashtabula, Ohio sequence occurred after the termination of the injection disposal well (Seeber et al., 2004).

Youngstown, Ohio. Research in Youngstown, Ohio began when over 100 earthquakes affected this area with no natural background seismicity. Kim (2013) explained Ohio has a natural earthquake zone called the Anna Seismic Zone. However, in the area of Youngstown, there is no record of earthquakes prior to 2011. After 2011 (onset of fluid injection), earthquakes began occurring near the injection disposal well site and radiated outward over time. The researchers clearly mapped a radial pattern of earthquakes with the disposal well in the center of the circle. Kim (2013) concluded the increase in pore pressure in the subsurface due to wastewater injection spread outward from the disposal well, inducing earthquakes in the affected region. Again, the earthquakes did not stop entirely after the disposal well shut down: seismicity continued to decrease steadily over the following months (Kim, 2013).

Azle, Texas. In 2013, seismic activity increased near Azle, Texas. Multiple injection wells were used to dispose wastewater into the Ellenberger formation; which is comprised of dolomite lying directly above crystalline basement rock. Hornbach et al.

(2015) emphasize the importance of obtaining baseline pressure (bottomhole), and permeability values, while constantly monitoring fluid rates and volumes throughout the injection process. The authors explain the Texas Railroad Commission does not keep a record of bottomhole pressures; therefore, they attempted to model the changes in subsurface pressure in the Azle area. The authors validated pressure increases within the area capable of producing an increase in seismicity through subsurface pressure modeling.

Fashing, Texas. Frohlich and Brunt (2013) published research on earthquakes originating in the Eagle Ford Shale in Texas near the city of Fashing. The Eagle Ford Shale is an unconventional reservoir containing large amounts of oil and natural gas; thus, well operators implement fracking to release the resources. The authors examined 14 hypocenters of a specific earthquake sequence and found a correlation between ten of the hypocenters and injection disposal wells. However, there was no correlation between four of the hypocenters and injection disposal wells. This led to mixed results. The authors concluded a possible correlation exists between earthquakes and wastewater injection, but the four uncorrelated earthquakes caused doubt (Frohlich & Brunt, 2013). The authors concluded the earthquakes in Fashing were induced, but through fluid extraction and not injection. It is possible the injection process contributed to the overall increase in seismicity, but the subsurface pressure reduction from the extraction process exceeded injection pressure (Frohlich & Brunt, 2013). The authors recognized a detailed analysis of subsurface hydrogeologic parameters would help support their findings.

Cogdell, Texas. Saltwater disposal has occurred in the Cogdell Oil Field since 1956 (Davis & Pennington, 1989). The seismicity near Snyder, Texas and within the

Cogdell Oil Field was determined induced, even though seismic swarms did not occur until 20 years after injection commenced (Davis & Pennington, 1989). In 1971, industries started injecting CO_2 into the same Canyon Reef limestone used for saltwater disposal. Gan and Frohlich (2013) found gas injection could be responsible for increased seismicity for the first time. These researchers suggest extensive modeling of subsurface stress and hydrogeology would help explain why the Cogdell Oil Field experiences earthquakes while surrounding regions are not. Gan and Frohlich (2013) researched injection disposal wells with rates equal to those correlated to seismic events that did not have earthquake hypocenter within 5.0 km (3 miles) of the well. Gan and Frohlich concluded these wells were not in the near vicinity of a fault. However, the author did not have enough data of the subsurface structure to be able to definitively support this hypothesis (Gan & Frohlich, 2013).

Dallas/Fort Worth, Texas. Frohlich (2012) conducted a correlation study in the Barnett Shale, an unconventional oil and gas play in Texas. In the Barnett Shale study, Frohlich (2012) examined 24 hypocenters occurring near the Dallas/Fort Worth International Airport. This study found all 24 were within 3.5 km (2 miles) of injection disposal wells. From this research, Frohlich (2012) determined wastewater injection into the Barnett Shale caused the 24 seismic events. Additionally, a critical injection rate of 150,000 BWPM (24,000 m^2/month) was correlated to each major seismic swarm. Frohlich (2012) acknowledges the critical rate will depend on site-specific subsurface properties.

Timpson, Texas. A 4.8 magnitude earthquake occurred near Timpson, Texas in 2014. The earthquake caused damage to several houses and woke up residents as far as

50 km (31 miles) away from the epicenter. With two high volume injection wells within 3.0 km (2 miles) of the earthquake swarm, researchers began investigating the cause of the Timpson seismicity. They found although sufficient evidence exists to correlate injection to the increase in seismicity, they could not rule out natural causes within this location (Frohlich et al., 2014). The authors recognize a more complete understanding of subsurface properties such as hydrogeology and stress conditions would provide a better understanding of the connection between seismic events and fluid injection (Frohlich et al., 2014).

Central Oklahoma. Keranen et al. (2013) closely examined a specific earthquake sequence from 2011 in Oklahoma. The sequence included three earthquakes with moment magnitudes of 5.0 or greater, the largest being a 5.7. The largest event caused structural damage at the epicentral region and two human injuries. At least 17 states felt the earthquake. The 5.7 earthquake near Prague, Oklahoma is the largest induced seismic event in U.S. history (as of March, 2016). Oklahoma has experienced a 200-fold increase in earthquakes since 2009 (Walsh & Zoback, 2015). Most of the research for this event was retroactive, meaning the authors used aftershocks to locate the focus of each major earthquake. The researchers deployed seismometers 24 hours after the initial 5.7 earthquake affected the area. Data from over 1,000 aftershocks provided the location for the earthquake hypocenters within the Wilzetta fault zone. The Wilzetta fault zone lies within the Wilzetta Oil Field, and the three major earthquakes originated within five kilometers of an injection disposal well. The wastewater injection into the injection disposal well began in 1993, which is 17 years before the first noted earthquake occurred in Oklahoma. Using the Davis and Frohlich (1993) criteria for induced seismicity, the authors concluded the cause of the 2011 major seismic event in Oklahoma was most likely, but not definitively, wastewater injection into Class II injection disposal wells (Keranen et al., 2013).

An opposition statement exists regarding the Prague, Oklahoma earthquake sequence. Keller and Holland (2013), as representatives of the Oklahoma Geological Survey and in collaboration with the Oklahoma Corporation Commission, issued a brief statement on the Prague earthquakes. The authors explain how the Wilzetta fault zone has a history of earthquakes: Swarms of earthquakes, such as the Prague event, are natural to the area. The authors declare fluid injection began in 1955 preventing the correlation of fluid injection to the earthquake swarm. Keller and Holland (2013) conclude the earthquake swarm in Prague was no more than a naturally occurring event, but continued monitoring would provide more insight into this event.

Sumy, Cochran, Keranen, Wei, and Abers (2014) conducted an additional study on the Oklahoma earthquakes. The researchers looked at the intensity of the earthquakes and the Coulomb failure criteria of the Prague, Oklahoma earthquake sequence. The team concluded the three earthquakes with magnitudes of 5.0 and higher resulted from Mohr-Coulomb stress failure within the adjacent rock structures and triggered several additional earthquakes. Results from the team's research imply the seismic hazard, or risk assessment, for induced seismicity may be greater than previous estimates.

Northern Oklahoma and Southern Kansas. Research with the region of Northern Oklahoma and Southern Kansas is in its infancy. The Mississippi Limestone (directly above crystalline basement) is the target injection interval for this region, which lies across the Kansas and Oklahoma border. Kansas started experiencing earthquakes in

2013. Rubinstein, Ellsworth, Llenos and Walter (2014b) suggested the earthquakes in Kansas might not be natural in origin. The USGS and Kansas Geological Survey have deployed additional seismic stations and are currently locating earthquake hypocenters (Buchanan, 2015). Monthly saltwater injection data are not available for Kansas (Walsh & Zoback, 2015). Walsh and Zoback (2015) provided injection rate and earthquake correlations among several locations in Northern Oklahoma. They concluded earthquakes in this region are likely associated with industrial activities, and preexisting geological conditions may be more indicative of predicting seismic magnitude than pore pressure (Walsh & Zoback, 2015).

Guy-Greenbriar, Arkansas. In Arkansas, Horton (2012) published research findings from yet another recent earthquake sequence. Unlike the other research articles, Arkansas has a strong history of earthquakes. The name of this active region is the New Madrid Seismic Zone (NMSZ). The NMSZ is the most seismically active region east of the Rocky Mountains. Evidence of paleoliquifaction in the region indicates earthquakes with magnitudes of seven or higher occurred within the last 1,100 years. After a 98% increase in earthquakes appeared within 6.0 km (3.7 miles) of disposal wells, the researchers began investigating the possibility of induced seismicity. The researchers measured seismicity before and after the installation of new disposal wells in the area in order to determine whether earthquakes were natural or induced. Due to known injection formation properties, such as rock type and fault lines, they knew the formations were directly connected to basement rock. The Arkansas Oil and Gas Commission ordered an emergency shutdown of the observed disposal wells after hundreds of small magnitude earthquakes appeared within 28 days of initial injection. The researchers verified induced seismicity by correlating initial injection with earthquakes, and by the significant reduction of earthquakes after the emergency shutdown. Earthquakes continued to shake the region even after the shutdown, mimicking the research from the Rocky Mountain Arsenal and Rangely Oil Field (Horton, 2012).

Summary

Each of the PISAs included within this research have experienced an increase in seismicity. Some of these locations are confirmed induced seismic areas, while other lack enough data to make scientific conclusions. The process of hydraulic fracturing includes a large volume of produced wastewater, which must be treated or disposed for public health and safety. Since subsurface injection is one of the most inexpensive options and is accepted by the EPA, it is the most often used disposal method by the industry. Hydraulic fracturing and wastewater disposal can cause several environmental issues, which are troublesome among concerned citizens. However, these industrial processes are beneficial to producing states and to the overall U.S. economy. If the U.S. is to continue supplying the national demand for natural resources such as natural gas, then it is imperative to find an environmentally and economically feasible solution the public can accept. Regulatory agencies and other monitoring entities must find a way to mitigate or even prevent seismic activity in regions of injection disposal. Additional data are required in structural, seismological, and hydrogeologic disciplines in order to make realistic decisions on how to manage seismic hazard.

CHAPTER III

EVALUATION OF HYDROGEOLOGIC DATA ASSOCIATED WITH USGS AREAS OF POTENTIALLY INDUCED SEISMICITY

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Abstract: The United States Geological Survey (USGS) identified seventeen U.S. locations experiencing an increase in seismicity, which may be potentially induced through industrial subsurface injection. These locations span across seven states, which vary in geological setting, industrial exposure and seismic history. Comparing the research across the seventeen locations reveals patterns for addressing induced seismicity concerns, despite the differences between geographical locations. A critical need exists for site-specific hydrogeologic data in order to determine potential hazards and manage risk. Most induced seismicity studies evaluate geologic structure and seismic data from areas experiencing changes in seismic activity levels, but the inherent triggering mechanism is the transmission of hydraulic pressure pulses. This research evaluates whether data are available in these locations to generate accurate hydrogeologic predictions, which could aid in managing seismicity. After analyzing peer-reviewed research within the seventeen locations, this research confirms a lack of site-specific hydrogeologic data for at risk areas. Commonly, formation geology data are available for these sites, but hydraulic parameters for the seismically active injection and basement zones are not. Obtaining hydrogeologic data would lead to better risk management for injection areas.

Keywords: induced seismicity, hydrogeology, pressure migration, subsurface injection

Introduction

Induced seismicity is a description used for seismic events linked to industrial processes such as hydrocarbon storage or wastewater disposal. This subsurface injection influences subsurface pressure, which impacts naturally occurring faults. When a fault reaches its critical stress threshold, as defined by the Mohr Coulomb stress failure criterion, earthquakes may occur (Nicholson & Wesson, 1990). The propagation of subsurface pressure originating from industrial injection disposal wells can induce seismicity (Healy et al., 1968; Herrmann et al., 1981; Nicholson & Wesson, 1990; McGarr et al., 2002; Ake et al., 2005; Herrmann et al., 2011; Horton, 2012). There are several areas within the midcontinent of the U.S. at risk for induced seismicity.

Earthquakes are possible in the midcontinent due to a high shear stress (Townend & Zoback, 2000; Peterson et al., 2014), meaning most areas within this region is at or near the strength limit for the crust. Any distress, large or small, applied to this high stress region can trigger an earthquake (Nicholson & Wesson, 1990; McGarr et al., 2002; Peterson et al., 2014). An increase in pore pressure at the fault surface creates a decrease in shear strength of the rock, thus increasing the chance for fault failure (Simpson, 1986; McGarr et al., 2002; Ellsworth, 2013).

The United States Geological Survey (USGS) announced in 2014 the locations of fourteen areas within the midcontinent, which may be linked to industrial injection processes (Petersen et al., 2014). Three additional areas were added to the USGS list in 2015, making a total of seventeen potentially induced seismic areas (PISAs) connected to industrial subsurface injection (Petersen et al., 2015). The seventeen PISAs were excluded from the U.S. National Seismic Hazard Model (NSHM) due to the anthropogenic influence (Peterson et al., 2015). The USGS recognizes more research in these seventeen areas is necessary to determine whether the increase in seismic events is a result of natural seismicity or is the result of industrial processes. This determination may range from scientific certainty, which is preferable, to preponderance of evidence standards depending on the availability of various data types. The determination of an area as seismically induced by anthropogenic processes is important, as it implies implementing risk management techniques could potentially reduce seismic risk.

In order to determine if an area is at risk for induced seismicity, researchers must compile a multidisciplinary data set. The data needed to investigate PISAs are comprised of structural geology (locations of faults and solid rock properties), seismology (seismic data and stress thresholds of faults), and hydrogeology (pressure migration and pathway from the injection well location to the critically stressed fault). Individually, each discipline can create predictive models about PISAs. While these three disciplines can conduct modeling of field data individually, the modeling and predictions based on their integration is what is required to effectively manage induced seismicity (Figure 3.1). When the models are integrated across the disciplines, the hazard prediction and scientific certainty for induced seismicity increases to allow improved risk management.

Although this research is interdisciplinary by nature, it is common for injection induced seismicity investigations to be approached through a structural or seismological perspective only. Locating hypocenters, determining the stress load of nearby critical faults, and mapping distances to injection well locations are all common practices in induced seismicity literature. However, subsurface pressure migration originating from an injection disposal well is a critical component of injection induced seismicity evaluations; hydrogeologic data appears to be underrepresented in research efforts.

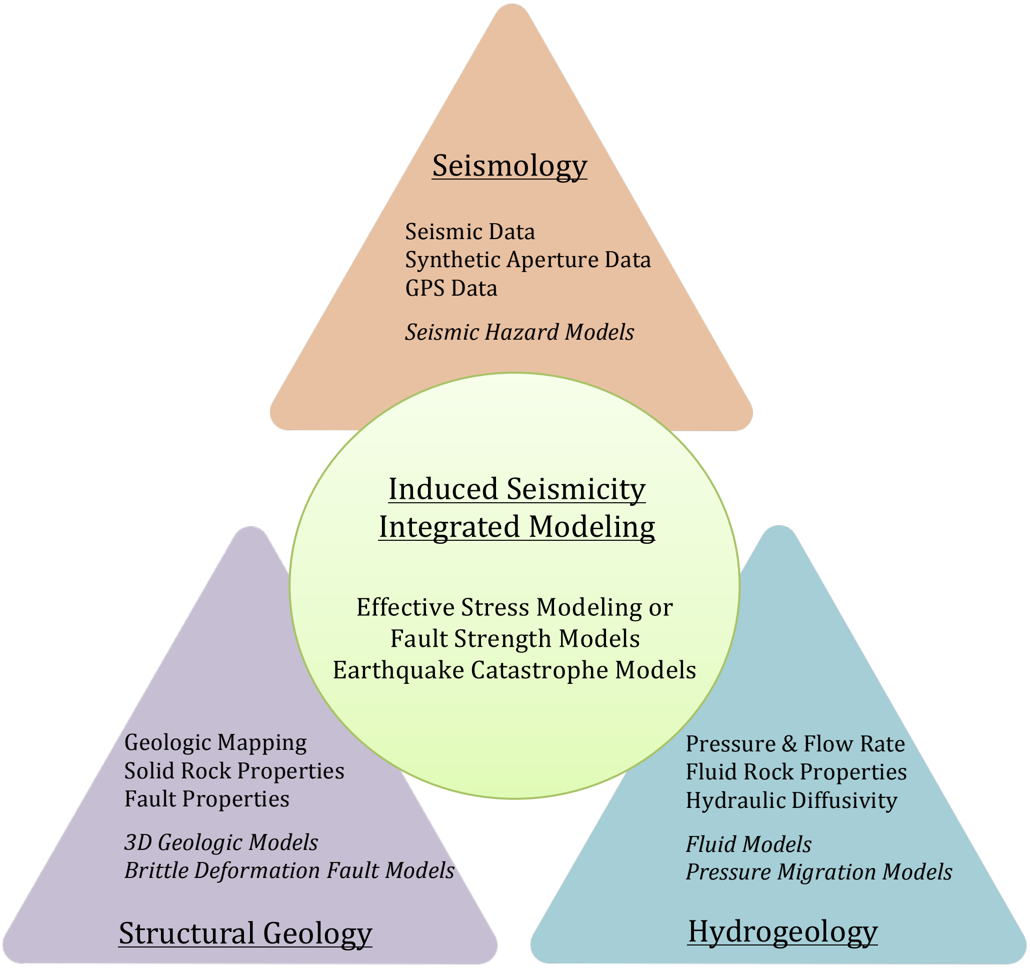

Figure 3.1. There are three main disciplines required to understand induced seismicity: seismology, structural geology, and hydrogeology. Each discipline has data and models (italicized) contributing to induced seismicity research. More hydrogeologic data is required to investigate areas of potentially induced seismicity. Together, these disciplines could produce effective stress models, fault strength models, or earthquake catastrophe models, which would contribute to the overall understanding of induced seismicity.

The research regarding injection induced seismicity is extensive, spanning across original descriptions of induced seismicity (Simpson, 1986) to case studies of injection induced seismicity (Ellsworth, 2013). Different approaches exist among researchers investigating induced seismicity in order to classify a location as industrially induced. In an attempt to standardize the classification process, Davis and Frohlich (1993) developed a set of questions designed to assist researchers in determining induced seismicity. The questions address characteristics such as background seismicity, temporal and spatial correlations, and injection practices. Nicholson and Wesson (1990) provide conditions including high stress faults, fault locations, proximity to injection disposal wells, injection pressures, and hydrologic properties of the injected interval as criteria for determining induced seismicity.

Seismic research within the U.S. has confirmed injection induced seismic events beyond a reasonable doubt in locations such as Rangely and Rocky Mountain Arsenal, Colorado (Healy et al., 1968; Raleigh et al., 1976). However, the level of certainty to which induced seismicity has been proclaimed varies among the USGS PISAs. As a matter of evidence, this would range from cases of probable cause (less than 50% certainty) to beyond a reasonable doubt (greater than 95% certainty). Keranen et al. (2013) explained hydraulic data such as reservoir pressure, formation permeability, and injection fluid volume are needed to link a seismic outbreak in Prague, Oklahoma to subsurface injection. Similarly, results in the Dagger Draw Oil Field indicated a lack of data regarding wellhead pressures, fluid injection, and earthquake numbers and strengths to be able to conclusively invoke an induced seismicity mechanism (Sanford et al., 2006). Researchers investigating increased seismicity in Brewton, Alabama, explained the difficulty in identifying induced seismicity without knowing the fluid properties, movement of subsurface pressure, and material properties (Gomberg & Wolf, 1999).

A lack of hydrogeologic data remains a consistent theme among research efforts that did not classify the origin of increased seismicity with scientifically clear and convincing evidence. This is reflected in the recent literature emphasizing the lack of hydrogeologic data and the need for subsurface formation properties to enhance induced seismicity research (Ellsworth, 2013; McGarr et al., 2015). The frequency in which the critical need for hydrogeologic properties is stated led to this investigation of the seventeen USGS PISAS and the completeness of these data. Additionally, research regarding the USGS PISAs is compartmentalized by location and this investigation looks across the seventeen locations to potentially identify patterns across various geological settings.

Hydrogeology for Injection Induced Seismicity

Evaluating pressure migration. In order to calculate the pressure change and travel time it takes for injection fluid to trigger a seismic event, the hydrogeologic characteristics of the injected area must first be identified (Davis & Pennington, 1989). The injected fluid does not have to physically touch a fault to trigger an earthquake, as only the pressure pulse must arrive and the change may be small (Mulargia & Bizzarri, 2014). Therefore, it is important to determine the movement of subsurface pressure changes originating from the injection well. Davis and Pennington (1989) used the Theis equation to determine pressure migration. This equation utilized data on well injection rate and construction, hydrogeologic properties of the formation (intrinsic permeability and storativity), and formation geometry. With adjustments to accommodate site-specific conditions, the Theis equation has often been used to calculate the propagation of pressure waves in the subsurface (Ferris, 1952; Lee & Wolf, 1998; Saucier et al., 2009; Cihan et al., 2011). This approach assumes a homogeneous, isotropic hydrologic continuum with an infinite lateral extent being injected at a constant rate. More complicated well hydraulic equations can be utilized, but the fundamental hydraulic parameters largely stay the same if continuum approaches are utilized. The well function providing the geometry of the hydrogeologic setting is the common change in more complicated equations. Obtaining the parameters necessary to implement the Theis equation allows for a better understanding of subsurface pressure migration; therefore, allowing more accurate predictions of potential seismic hazard.

Pressure measurements. Davis and Pennington (1989) explain bottomhole pressures at the injection site are important, but they are not typically helpful when used in isolation; the pressure analysis for the entire injection interval could be inaccurate. Obtaining baseline pressure rates and consistent pressure measurements throughout the injection interval may help establish a connection between injection wells and earthquake hypocenters. An injection well pumping into a low-pressure formation may be directly connected to a high-pressure system with a critically stressed fault (Davis & Pennington, 1989). Subsurface pressure pathways can be classified in two broad-spectrum categories: diffusive and advective. Diffusive pressure migration moves through the injected subsurface matrix in a relatively uniform manner, similar to the ideal hydrological model of a homogenous and isotropic media. Advective migration exists within fractured systems, where the pressure front moves along pathways within the fractured media. Advective migration is particularly important when injecting into or near basement, which can be highly fractured and provide hydraulic flow pathways to critically stressed faults (Healey et al., 1968; Horton, 2012). Since it is unrealistic to assume all injected formations are homogenous and isotropic, and it is difficult to determine how fractured the system is without testing, the need for monitoring away from the injection well site location is easily justified. Useful pressure measurements include data distal from the well and throughout and below the injected formation to gain a quantitative understanding of pressure migration away from the injection zone. This monitoring is rarely done, as the cost of monitoring wells at injection depths is considered prohibitive in the absence of seismicity.

Rate and volume. Throughout the literature, the terms volume and rate are often used interchangeably. There is a strong distinction between these two terms in not only definition, but also their influence on pressure performance and injection regulation. If the injection interval is underpressured, the formation may allow for a higher volume of fluid to be injected into the formation. The critical monitoring factor in an underpressured system becomes injection rate as the formation can potentially withstand high volumes of fluid, but the pressure migration signature moves outward. The rate of injection must be monitored to keep track of the pressure migration away from the well. The hazard for this scenario would be nearby critically stressed faults. This is supported by the conclusions of Weingarten et al. (2015) that injection rate is the most important factor to address induced seismicity. Alternatively, if the injection interval is overpressured, the interval may not be able to withstand additional pressure into the system. At this point, volume becomes the critical monitoring factor. The importance of capturing injection volume is emphasized in quantifying the maximum magnitude earthquake induced from fluid injection (McGarr, 2014). Injection volumes may surpass the elastic limit of the formation, causing deformation. In a regulatory context, a well of interest must be abandoned if a volume limit is attained. If rate is the factor, the well may be able to continue operating at a reduced rate.

Hydrogeologic Data Review

The National Research Council identified 48 locations within the U.S with observed occurrences of induced seismicity due to the hydrocarbon retrieval process or wastewater injection (NRC, 2013). This research investigated the available hydrogeologic data across the seventeen USGS identified PISAs, as the U.S. government specifically recognizes them as locations for potentially induced seismicity. This U.S. dataset maintained similar regulatory settings among the locations with various geologic settings (Peterson et al., 2015). The NSHM identified research efforts supporting the classification of the seventeen PISAs. This investigation focused on those research efforts and included supplementary peer-reviewed articles within the seventeen PISAs. All but one of the seventeen PISAs has at least one peer-reviewed research investigation available for reference as of March 2016 (see Table 3.1).

The research was reviewed for the aforementioned hydrogeologic characteristics (hydrogeologic formation parameters, injection interval pressure measurements, and injection rate over time), as their influence on pressure migration predictions is essential. Where possible, values were obtained for injection well characteristics (injection rates, volumes, baseline injection pressure, and peak injection pressure) and injection interval characteristics (lithology, depth, thickness, porosity, permeability, transmissivity, and storage). To address the need for collecting hydrogeologic data throughout the formation, the maximum distance of earthquake swarms from targeted injection wells was tabulated to see if trends exist. Data compilation also included whether the literature indicated a history of active seismicity and if industrially induced seismicity was confirmed in each area.

The scientific certainty of each evaluation was also included in the results as this is variable across the literature. The terminology was the same as utilized for evidence in the judiciary system. *Probable Cause* was used when the reference and available data suggested induced seismicity might be a problem, but evidence was lacking or indicated a potential natural source of seismic changes. *Preponderance of Evidence* indicated sufficient evidence of correlation and injection rate and volumes supported induced seismicity as likely with a greater than 50% probability. These data were increased to *Clear and Convincing* if injection was decreased or discontinued and seismicity decreased or returned to background over time, attaining near 90% certainty. *Beyond a Reasonable Doubt* was used for cases like Rangely, CO where the earthquake patterns were modified on short time scales indicating certainty greater than 99%.

Results

An overview of the available hydrogeologic data for the seventeen USGS PISAs is provided in Table 3.1. The most prevalent quantitative hydrogeologic data available for quantifying PISAs includes injection fluid volumes and rates, with 100% of peer-reviewed references reporting these data (Greely, CO was removed from the hydrogeologic data results as there was no peer-reviewed literature for this PISA as of March 2016). Some exact values for rate or volume were not explicitly provided within the literature. In these cases, researchers included rate or volume for analysis, which implies these values were available for investigations. Injection volume and rate are collected from state agencies and provided to individuals upon request.

Formation pressure data vary across the peer-reviewed PISAs. Baseline regional pressure measurements for the injection interval obtained prior to well completion are absent across the literature, with the exception of the earthquake experiment at Rangely, CO.

Table 3.1
Existing Hydrogeologic Data Within the 17 USGS Potentially Induced Seismic Areas

USGS PISA	Rate	Volume	Baseline Pressure	Formation Thickness	S	T	K	Reference
Brewton, AL	✔	✔	X	X	X	X	X	Gomberg & Wolf (1999)
Guy-GreenBriar, AR	✔	✔	X	≈	≈	≈	✔	Horton (2012)
RMA, CO	✔	✔	≈	≈	≈	✔	X	Evans (1966); Healy et al. (1968); Hsieh & Bredehoeft (1981)
Raton Basin CO/NM	✔	✔	≈	✔	X	X	X	Meremonte et al. (2002)*; Rubinstein et al. (2014a)
Rangely, CO	✔	✔	✔	✔	X	✔	✔	Raleigh et al. (1976)
Greeley, CO	-	-	-	-	-	-	-	Yeck et al. (2014)* No peer-reviewed research
Paradox Valley, CO	✔	✔	X	✔	X	✔	✔	Ake et al. (2005); Block et al. (2014)
Dagger Draw, NM	✔	✔	X	X	X	X	X	Sanford et al. (2006); Pursley et al. (2013); Herzog (2014)
Youngstown, OH	✔	✔	≈	✔	X	X	X	Kim (2013)
Ashtabula, OH	✔	✔	X	X	X	X	X	Seeber et al. (2004)
Central OK	✔	✔	X	✔	≈	≈	X	Keranen et al. (2013); Keranen et al. (2014)
North OK/South KS	✔	✔	X	X	X	X	X	Rubinstein et al. (2014b)*; Gobel (2015); McNamara et al. (2015)
Azle, TX	✔	✔	≈	✔	≈	X	✔	DeShon et al. (2014)*; Hornbach et al. (2015)
Fashing, TX	✔	✔	≈	≈	X	X	✔	Pennington et al. (1986); Davis et al. (1995); Frohlich & Brunt (2013)
Cogdell, TX	✔	✔	≈	✔	≈	X	≈	Davis & Pennington (1989); Gan & Frohlich (2013)
Dallas-FTW, TX	✔	✔	X	✔	X	X	X	Frohlich et al. (2010); Frohlich et al. (2011); Frohlich (2012)
Timpson, TX	✔	✔	X	X	X	X	X	Brown & Frohlich (2013)*; Frohlich et al. (2014)

✔ The authors in the study took direct measurements themselves or used direct measurements from state agency, or other research article, with site-specific data for their location.
≈ Used measurements from a different location not specific to the research area, or values are estimated/approximated by the authors and used in methodology.
X The author(s) did not present the parameter in the research article.
K=Hydraulic Conductivity; S=storativity or porosity, T=transmissivity

A total of 44% of the articles provided baseline formation pressure values; all of which were estimated, assumed, or calculated, with 0% reporting physical measurements. Surface and bottomhole pressure measurements after well establishment are prevalent in the literature with 75% of articles reporting these values. Keranen et al. (2013) were able to provide wellhead pressures prior to injection, but this measurement is not the baseline for the formation as previous hydrocarbon production in the same location affected the pressure measurements. Hornbach et al. (2015) explained the Texas Railroad Commission does not require bottomhole formation pressure measurements and only wellhead pressures are recorded. Peak pressure values across the PISAs ranged from 2 MPa to over 40 MPa, with 75% of research efforts reporting a peak injection pressure. Researchers for Rangely, CO, were able to retrieve baseline pressure measurements for the injection interval at the well site, and obtained pressure measurements throughout the injected formation to evaluate the pressure migration originating from the injection well (Raleigh et al., 1976).

Fifty percent of the articles referenced the specific formation used for injection, therefore injection interval thickness values are provided mostly as formation depth ranges. In 31% of the articles, researchers who do not report thickness values either do not mention injection interval depth descriptions or report the injection interval depth range, leaving the thickness parameter absent within site-specific formation descriptions. Injection interval thickness was estimated in 19% of the articles.

Hydraulic parameters for flow (permeability, hydraulic conductivity or transmissivity) and storage (porosity, specific storage, storativity) are the least prevalent parameters within the literature. When available, hydraulic conductivity values are often reported as permeability, which is expected as these locations have variable phases and fluid densities. Permeability is a considered a stable parameter in these locations; hydraulic conductivity is not. Any described hydraulic conductivity values were noted under permeability values in Table 3.1. A total of 37% of the articles reported a physical measurement for injection interval flow at their site and 13% of flow values were estimated. Fifty percent of the articles did not report flow values for the injection interval. Nineteen percent of the 17 PISAs had physical transmissivity measurements, while 31% had permeability or hydraulic conductivity values. The other 50% of sites had no permeability data for the site.

Some research articles reported porosity or effective porosity values, which aid in determining storativity. However, storativity is affected by fluid properties, which is not captured by porosity values alone. Storativity was estimated in 31% of the articles, with no reported storage value measurements directly observed in the research. A special data point from Central Oklahoma was a value of hydraulic diffusivity used in their model of pore pressure migration, which is the ratio of transmissivity to storativity (Keranen et al., 2014). The ratio between transmissivity and storativity were estimated in Table 3.1 for research in Central Oklahoma.

In 94% of the USGS PISA articles, researchers stated the majority of earthquakes occurred within a maximum of 10 km (6.2 miles) of injection wells. The researchers in Paradox Valley recognized earthquakes occurred as far as 17 km (10.6 miles) away from injection sites, but concluded the majority of hypocenters within 4.5 km (2.8 miles) of target injection wells (Horton, 2012). Likewise, researchers at Rocky Mountain Arsenal located hypocenters 75 km (46.6 miles) away, with the majority occurring within 8 km (5 miles) of injection wells (Healy et al., 1968). Central Oklahoma is one of the largest PISAs with significantly more injection wells within the research area, affecting the overall seismic activity. Researchers in this area estimated hypocenters as far as 35 km (21.8 miles) away from targeted injection sites (Keranen et al., 2013).

Discussion

There is a clear lack of site-specific hydrogeologic data across the seventeen USGS PISAs; data necessary for calculating the subsurface pressure migration and in formation management. It is important to discuss why these missing data sets should be collected, since obtaining hydrogeologic data will assist researchers and site managers regarding the following issues: 1.) To determine whether an area is industrially induced; 2.) For risk assessment for current and future seismic hazard in areas classified as industrially induced; 3.) To apply appropriate mitigation techniques or management practices necessary to prevent associated seismic hazard in areas classified as industrially induced.

Hydrogeologic data. Rubinstein and Mahani (2015) explain seismic, geological, and industrial well data are necessary to establish mitigation techniques for areas of induced seismicity. The industrial component referenced consists of injection rates and bottomhole pressures at well locations. This is similar to the previously described multidisciplinary nature of induced seismicity research, except pressure migration predictions cannot be determined from well-site data alone. Transmissivity, storativity, and injection interval lithology and thickness must be captured to measure and predict pressure migration. It is critical to determine a conceptual site model appropriate for defining the seismic hazard. Is the injection interval or the basement formation best simulated as a fractured system or as a porous continuum? Is the injection interval or the basement formation underpressured or overpressured? Data to build a sound quantitative conceptual model is key for management.

Injection rates and volumes appear widely accessible in all of the areas evaluated. However, researchers must understand these data must be requested and are not always readily available for research endeavors. Retrieving these data sets from state agencies can often take several months to obtain and may not be in a standardized format for analysis. McGarr et al. (2015) discussed the importance for industry to disclose injection data and characteristics of the injection interval in order to properly investigation seismic risk and mitigation. The current monitoring regulations for injection disposal wells only cover fracture pressure, total injection volume, and average injection pressure (Ellsworth, 2013). This is reflected in the available published data for these sites (Table 3.1). If the other hydrogeologic properties were required for monitoring, it is possible these data would be as widely accessible as injection rates or volumes.

In the absence of industrial data sets, measurements can be physically obtained throughout the injected reservoir in order to capture the necessary parameters to calculate pressure migration. The wide range of peak injection interval pressures across the seventeen PISAs emphasize the importance of baseline pressure as a useful parameter in determining the change in stress conditions in a given location. Since this research confirms the need for hydrogeologic data, it is recommended to conduct hydraulic tests throughout the injection interval within at least a 10 km (6.2 mile) radius of injection wells to assess the subsurface conditions before, during and after injection occurs. The maximum distance of earthquakes surrounding injection wells, as found in the majority of PISA research results, justifies the distance for these tests. If testing is required as part of well installation, the dataset from installed wells can be used to build up reservoir properties and inactive wells can be utilized for monitoring.

Some of the parameters are often calculated or estimated from the existing data from a different geologic region. For example, the Guy-Greenbriar injection wells were injecting into formations hydraulically connected to Precambrian basement and referenced the transmissivity value from the Precambrian basement rock from Rocky Mountain Arsenal. The rock body, the stress field, and the fracture orientation and distribution might be strongly different, but a simple assumption of having similar conditions was utilized due to a dearth of data. Additional research includes estimating the pressure migration using calculated or estimated hydrogeologic values in locations among the seventeen PISAs having sufficient data to accomplish the estimation. While this is appropriate in the absence of available data to retroactively evaluate the seismic potential of an area, it should not be considered appropriate for approval of new disposal wells.

Both Keranen et al. (2014) and Hornbach et al. (2015) were able to develop pressure models predicting the movement of pressure away from injection wells. Values for formation thickness were measured and hydrogeologic properties such as permeability and storativity were estimated. They superimposed earthquake hypocenters over the model to support pressure migration and its association with seismic events. If the hydrogeologic parameters were known for a specific location, this type of modeling could be developed for locations not only after an earthquake sequence occurs, but also prior to onset of injection to identify areas at risk for seismicity and potentially reduce induced seismic hazard. Since earthquakes can continue to occur long after injection ceases (Healy et al., 1968), this type of model would be beneficial in areas currently experiencing induced seismic events to predict how long the area could expect the pressure migration to expand.

Determining induced vs. natural seismicity. Rangely, CO, the only PISA classified as induced seismicity beyond a reasonable doubt, had consistent hydrogeologic data available for support. However, some locations were able to determine the cause of seismicity was due to subsurface injection with clear and convincing evidence and without obtaining detailed hydrogeologic data. Since hydrogeologic data are critical components of determining induced seismicity and are predominantly missing throughout these locations, to what degree of certainty is induced seismicity claimed? The experiment at Rangley, in particular, was able to repeatedly manipulate the seismic activity by turning the injection disposal well on and then pumping back to turn seismicity off. This case holds a high degree of certainty, or *Beyond a Reasonable Doubt* as claimed in Raleigh et al. (1976, p. 1235).

Table 3.2
Induced Seismicity Status Within the 17 PISAs

USGS PISA	Confirmed History of Natural Seismicity?	Determined As Induced Seismicity?	Degree of Scientific Certainty Based on Research?
Brewton, AL	No	No	*Probable Cause*
Guy-GreenBriar, AR	Yes	Yes	*Clear and Convincing*
RMA, CO	Yes	Yes	*Clear and Convincing*
Raton Basin' CO/NM	Yes, Low level	No	*Probable Cause*
Greeley, CO	No	Likely	*Probable Cause*
Rangely' CO	No	Yes	*Beyond a Reasonable Doubt*
Paradox Valley, CO	No	Yes	*Clear and Convincing*
Dagger Draw, NM	Yes	Yes	*Probable Cause*
Youngstown, OH	No	Yes	*Clear and Convincing*
Ashtabula, OH	Yes, Low level	Yes	*Clear and Convincing*
Central OK	No	Likely	*Preponderance of Evidence*
North OK/South KS	No	Likely	*Probable Cause*
Azle, TX	No	Yes	*Preponderance of Evidence*
Fashing, TX	No	Yes	*Preponderance of Evidence* (for

			production) & *Probable Cause* (for injection)
Cogdell, TX	No	Yes	*Preponderance of Evidence*
Dallas-FTW, TX	No	Yes	*Clear and Convincing*
Timpson, TX	Yes, Rarely	Yes	*Preponderance of Evidence*

Probable Cause – Seismic correlation with onset of injection only
Preponderance of Evidence – Seismic correlation to injection rate and/or volume
Clear and Convincing – Seismic correlation with cessation or drastic decrease of injection
Beyond a Reasonable Doubt – A repeatable direct seismic correlation to onset or cessation of injection

The Guy-Greenbriar research location used the direct correlation between the shut down of an injection disposal well and a reduction in seismic activity to claim induced seismicity (Horton, 2012). This location had an emergency shutdown enforced on the disposal wells and did not have access to the injection well to elevate results through repetitive testing. The evidence in this location could be classified as *Clear and Convincing*. The location was only at a level of *Preponderance of Evidence* before decreasing in seismicity once the wells were shut in. The locations of Dallas/Ft. Worth, Ashtabula, Youngstown, Paradox Valley, and Rocky Mountain Arsenal experienced similar decreases in seismic activity after wells ceased injection or during a hiatus or reduction in injection.

Central Oklahoma, Timpson, and Azle, the locations classified as *Preponderance of Evidence,* used lines of evidence such as no previous seismicity in the area, proximity of wells to hypocenters, high rates of injection, or a correlation between earthquake occurrences and onset of injection. These lines of evidence are useful in determining induced seismicity, but lack the pressure pathway connecting a disposal well to earthquake hypocenters. In research areas classified as *Probable Cause* for induced seismicity, there remains too little hydrogeologic data, preexisting seismic occurrences, or limited spatiotemporal correlations within the peer-reviewed literature to make conclusions of induced seismicity. Table 3.2 classifies each of the areas into perspective degrees of certainty, based on data available and research efforts within each location.

This degree of certainty is important, because there must be a uniform classification across PISAs in order to assess the risk imposed by induced seismicity. Obtaining hydrogeologic data will only enhance understanding of induced seismicity and categorize locations with a specific degree of certainty. Providing hydrogeologic descriptions of the injection interval may facilitate the classification process. We cannot hope to address risk assessment without first quantifying the components affecting the system.

Risk assessment. The NSHM provides a scientific approach to earthquake hazard prediction and facilitates structural plans for buildings, the creation of mitigation strategies, and emergency preparations for earthquake hazards. However, the USGS removed the seventeen PISAs from the NSHM due to the implications of induced seismicity. To address and reduce the risk posed by induced seismicity, some locations chose to simply shut down injection wells. Although effective, this response does not provide a proactive approach to addressing induced seismic risk before the hazard strikes, and it does not address the continuing risk of earthquake occurrence after injection ceases. With additional hydrogeologic data, one could potentially determine the risk posed by injection disposal wells by understanding the pressure propagation in a specified injection interval.

Mitigation. McGarr et al. (2015) describe a set of challenges faced when addressing induced seismicity. One of the challenges in mitigating the effects of seismicity is the delay of seismic activity from the onset of injection. McGarr et al.

(2015) state the analysis of earthquake rate change will help us better understand this challenge. In addition to this statement, this research supports the importance of obtaining hydrogeologic data in induced seismicity research in order to calculate how fast the fluid or pressure pulse will migrate away from the injection well, thus allowing for predictions of the time it would take to reach a critical fault, if at all.

Conclusion

This research found a considerable lack of hydrogeologic data available across the seventeen USGS identified PISAs. Injection rates and volumes are widely accessible due to the regulatory requirements for injection wells. Regulating the collection of quantitative hydrogeologic descriptions may make these data more accessible. Hydrogeologic data can facilitate the classification of PISAs and provide a higher level of scientific certainty by identifying hydraulic pathways from injection wells to critically stressed faults. The availability of hydrogeologic data could potentially enhance induced seismicity research efforts, mitigation techniques, and injection site descriptions before, during, and after subsurface injection well completion.

The results of this research indicate an apparent lack of baseline injection formation pressure prior to well establishment. This lack of baseline data indicates a critical need for hydraulic characterizations of injection locations before well establishment, in order to determine whether a location is conducive for deep injection disposal. Establishing the viability of potential injection locations is crucial in the prevention of induced seismic hazard.

The necessity of hydrogeologic data cannot be overstated. If the goal of induced seismicity research is to discover the origin of increased seismicity and this determination relies on an understanding of subsurface pressure migration, then the hydrogeologic properties of the injection interval must be known. Furthermore, if induced seismicity is identified, an understanding of local pressure migration will allow for predictions to allow effective management of these seismic hazard zones.

CHAPTER IV

PATTERNS OF SEISMICITY ASSOCIATED WITH USGS IDENTIFIED POTENTIALLY INDUCED SEISMIC AREAS

Article Submission: Preparing manuscript for *Science*

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Abstract: Investigations regarding induced seismicity within the Central and Eastern United States included 17 potentially induced seismic areas identified by the USGS as at risk for induced seismicity. A systematic review of these locations was conducted in order to discover trends among earthquake distances from injection disposal wells and patterns of distance over time. Previous research indicates an average of 10 km (6 miles) where the majority of seismicity is expected to occur in locations suspected of induced seismicity. Some areas have found seismic events related to industrial activities at a much larger radius of 35 km (22 miles) to over 70 km (43 miles). This research isolated nine of the 17 locations where specific injection disposal wells were identified as potential contributors for induced seismicity. The distance between well sites and earthquake occurrences were found around each location and analyzed for trends between sites. Earthquake distances from wells were evaluated with duration of injection to determine if earthquakes migrate outward over time. Results indicate a radius of 48 km (30 miles) where ninety percent of felt earthquakes occur among these locations. Additionally, the analysis indicated the closest proximal felt seismic events, on average, occurred 2 km (1.5 miles) away from injection disposal wells.

Keywords: induced seismicity, hydrogeology, pressure migration, subsurface injection

Introduction

When an increase in subsurface pressure originating from injection disposal wells crosses a critically stressed fault, earthquakes may occur (Healy et al., 1968; Herrmann et al., 1981; McGarr et al., 2002; Nicholson & Wesson, 1990; Raleigh et al., 1976). Seismicity related to industrial fluid injection processes is referred to as induced seismicity (Nicholson & Wesson, 1990; Simpson, 1986). The National Research Council identified 48 U.S. locations associated with induced seismicity related to injection disposal wells (NRC 2013). The United States Geological Survey (USGS) removed 17 of these locations in early 2015 from the 2014 National Seismic Hazard Model (NSHM) due to the potential influence of induced seismicity (Petersen et al., 2014). These locations may be referred to as potentially induced seismic areas (PISAs). The 17 PISAs are located within the Central and Eastern United States (CEUS), where the continental crust is at or near the strength limit due to high shear stress within the region (Peterson et al., 2014; Townend & Zoback, 2000). This means increasing pore pressure by subsurface injection in this high stress region increases the chance of fault failure by reducing the overall strength of the rock (Ellsworth, 2013; McGarr et al., 2002; Simpson, 1986). The USGS continues to identify additional PISAs as more research becomes available. This research investigates earthquake distances from injection disposal wells from a hydrogeologic perspective.

Availability of Hydrogeologic Data

Injection rates and volumes are found extensively throughout the literature since these parameters are captured as part of routine injection well monitoring by most state regulatory agencies (Barnes & Halihan, in review). Injection rate is arguably the most critical parameter for investigating induced seismicity (Weingarten, 2015). Researchers explain the importance of capturing site-specific subsurface properties in order to identify key injection rates linked to induced seismicity (Davis & Pennington, 1989; Frohlich, 2012). It is important to use an interdisciplinary approach to investigate induced seismicity by using seismology, structural geology, and hydrogeology to fully understand the factors within a specific location (Barnes & Halihan, in review). Current literature regarding induced seismicity primarily focuses on seismology and structural geology, such as locating earthquake occurrences and correlating those with onset of injection. Hydrogeologic data, such as baseline pressure, flow rates, and storage of the injection interval are not consistently captured throughout induced seismicity investigations (Barnes & Halihan, in review). Hydrogeologic descriptions of the subsurface may allow for creating predictions of how injection rates and volumes would affect a given system. For example, if the pressure limit capable of triggering earthquakes is known in a specific location, injection wells and rates could be disbursed throughout the formation so the critical threshold is not surpassed in any one location (Davis & Pennington, 1989). Research in Texas suggests extensive modeling of subsurface stress and hydrogeology would help explain why the Cogdell Oil field is experiencing earthquakes while surrounding regions are not (Gan & Frohlich, 2013). The inherent mechanism for induced seismicity results from an increase of pressure migrating through the subsurface. Therefore, hydrogeologic parameters are necessary for measuring pressure migration in the subsurface and are vital to investigating and addressing issues in induced seismicity.

Pressure Migration

When fluid is injected into the subsurface, it increases the pressure placed on the pore spaces within the rock, decreasing the rock strength. The fluid itself does not have to reach the critically stressed fault in order for the increase in pressure to trigger an earthquake (Mulargia & Bizzarri, 2014). Tracking or modeling the propagation of pressure from injection will allow for better prediction of induced seismicity and regulation of injection well rates. Davis and Pennington (1989) successfully used the Theis equation to determine subsurface injection pressure migration rates (Theis, 1935). The transient Theis equation or steady state Thiem equation require knowledge of hydraulic parameters and injection rates to determine the pressure generated due to injection.

A typical well type curve for well drawdown over time found during an aquifer test using the Theis equation will show drawdown decreasing as distance increases for a production well or buildup increasing for an injection well. Intermittent injection or changes in the rate of injection create unsteady state conditions within the aquifer. For steady state where injection is held constant or flow within the aquifer has reached equilibrium, it is appropriate to use the Thiem equation. The Thiem equation is similar to the Theis equation except aquifer storage is not considered. These equations are capable of pressure migration through the subsurface. Unfortunately, hydraulic parameters such as formation storage and transmissivity are not readily available in current field research of induced seismicity. Analytical models demonstrating pressure migration patterns among PISAs is an appropriate solution in the absence of hydrogeologic data sets.

Models built from analytically estimating pressure movement could be compared to other established analytical trends, such as the Kaiser Effect. The Kaiser Effect is an expectation that earthquake occurrences over time should migrate away from injection sites (Baisch et al., 2010; Baisch & Harjes, 2003). A system reflecting the Kaiser Effect would indicate a decay of pressure migration over time; similar to a Theis or Thiem analysis of well drawdown.

Systematic Review

With the current data available for the 17 PISAs, does a trend exist among these locations indicating a distance where pressure differentials are expected to travel to generate felt earthquakes? Injection disposal wells with injection rates over 150,000 BWPM (24,000 m^3/mth) are sometimes associated with seismic activity approximately 3 km away from the well (Frohlich, 2012). Rangely, Colorado experienced over 900 earthquakes within a year, with 350 of those earthquakes occurring within 1.0 km (0.5 miles) of injection wells (Raleigh et al., 1976). On the Guy-Greenbriar fault in Arkansas, 98% of earthquake activity ($m \geq 2.0$) occurred less than 6.0 km (3.7 miles) of injection disposal wells within a two-year time period (Horton, 2012). A hydrogeologic model of a series of earthquakes in Oklahoma suggested an injection well 3.5 km (2 miles) away from the swarm of earthquake hypocenters injecting over 3 million BWPM was a major contributor to an increase in seismic activity (Keranen et al., 2014). Other research efforts within the 17 USGS PISAs concluded most earthquakes occurred within a 10 km (6 miles) radius of injection wells (Barnes & Halihan, in review). Yet earthquakes can occur at greater distances than 10 km within these locations. Paradox Valley, Colorado experienced earthquakes 17 km (10.5 miles) away from injection sites (Block et al., 2014). Central Oklahoma had earthquake occurrences 35 km (22 miles) away from target injection wells (Keranen et al., 2013), while Rocky Mountain Arsenal had earthquakes 75 km (46.6 miles) away (Healy et al., 1968).

It is difficult to determine the extent injection pressure will travel within a specific system without appropriate site conceptual models for each PISA. If an average distance of propagation could be found among the USGS identified locations, then management practices for seismically active locations could be modified until site-specific hydrogeologic data were available. The purpose of this investigation is to: (1) conduct a systematic review of the 17 PISAs identified by the USGS to search for trends among earthquake occurrences and distances from injection wells, (2) determine a proximal and distal distance the majority of earthquakes occur on average, and (3) evaluate if pressure propagation extending from injection disposal wells across differing geological areas follows patterns similar to those described by basic hydrogeologic principles.

Methodology

Compiling consistent data sets across multiple PISAs is difficult as each location has a different approach to investigating induced seismicity. The goal of any systematic review is to create a unified data set representing each location as accurately as possible, while allowing for comparisons between sites. Eight of the 17 PISAs were not conducive to this systematic investigation due to a lack of available data sets. As of March 2016, no peer-reviewed literature on Greeley, Colorado or the Northern Oklahoma/Southern Kansas locations were available to determine key injection well locations correlated to induced seismicity. The literature for Rangely, Colorado and Dagger Draw, New Mexico did not provide the spatial locations of the injection wells potentially associated with seismicity. The areas of Central Oklahoma, Fashing, and Cogdell, Texas have thousands of injection wells and numerous earthquake hypocenters within their respective areas, making it difficult to target specific injection wells due to the large scale and magnitude of earthquake activity. Rocky Mountain Arsenal's earthquake activity occurred prior to the recorded earthquakes within the USGS earthquake database archives. Nine of the 17 PISAs provided the data required for analysis, making them viable locations for this research. The 17 USGS identified PISAs used for this research, references for peer-reviewed research within each location, and the status of available injection well data within the literature are listed in Table 4.1.

Table 4.1
Descriptions of Available Injection Well Data Within 17 USGS Identified PISAs

USGS PISA	Reference	Available Data
Brewton, AL	Gomberg & Wolf (1999)	Injection well locations provided
Guy-GreenBriar, AR	Horton (2012)	Injection well locations provided
RMA, CO	Evans (1966); Healy et al. (1968); Hsieh & Bredehoeft (1981)	Earthquake occurrences not available through USGS database
Raton Basin CO/NM	Meremonte et al. (2001)*; Rubinstein et al. (2014)	Injection well locations provided
Rangely, CO	Raleigh et al. (1976)	Injection well locations not provided
Greeley, CO	Yeck et al. (2014)*	No peer-reviewed research available
Paradox Valley, CO	Ake et al. (2005); Block et al. (2014)	Injection well locations provided
Dagger Draw, NM	Sanford et al. (2006); Pursley et al. (2013); Herzog (2014)	Well locations not provided
Youngstown, OH	Kim (2013)	Injection well locations provided
Ashtabula, OH	Seeber et al. (2004)	Injection well locations provided
Central OK	Keranen et al. (2013); Keranen et al. (2014)	Numerous well locations; could not determine specific injection wells potentially responsible for seismic increase
North OK/South KS	Rubinstein et al. (2014)*; Gobel (2015); McNamara et al. (2015)	No peer-reviewed research available providing well locations
Azle, TX	DeShon et al. (2014)*; Hornbach et al. (2015)	Injection well locations provided
Fashing, TX	Pennington et al. (1986); Davis et al. (1995); Frohlich & Brunt (2013)	Numerous well locations; could not determine specific injection wells potentially responsible for seismic increase
Cogdell, TX	Davis & Pennington (1989); Gan & Frohlich (2013)	Numerous well locations; could not determine specific injection wells potentially responsible for seismic increase

Dallas/FTW, TX	Frohlich et al. (2010); Frohlich et al. (2011); Frohlich (2012)	Injection well locations provided
Timpson, TX	Brown & Frohlich (2013)*; Frohlich et al. (2014)	Injection well locations provided

The injection wells used in this research were selected because of their causal relationship with increased seismicity identified by peer-reviewed literature within the PISAs. Each well was either determined as solely responsible for the increase in seismicity, or part of a network of injection wells identified in the literature as contributing to seismic activity. Since these wells targeted by individual research efforts were identified as the highest contributing factors to localized induced seismicity, this research assumes other wells within each location are negligible. The locations of the wells were provided in the literature and are listed in Table 4.2 (well names were removed). The coordinates of well locations were used when a single well was responsible for the increase in earthquake activity. In areas where multiple wells were thought to be the cause of the increased activity, an average of coordinates were calculated to find a central location among the wells. The radius of injection wells for multiple well locations is listed in Table 4.2 providing the furthest well locations from the calculated central point.

Table 4.2
Injection Well Locations

USGS PISA	Well	Latitude	Longitude	Central Latitude	Central Longitude	Distance Away from Central Location (km)
Brewton, AL	1	31.07	-87.368	31.07	-87.368	0 km
Guy-GreenBriar, AR	1	35.32	-92.3	35.28	-92.3	4.26
	2	35.26	-92.41	35.28	-92.3	9.92
	3	35.27	-92.3	35.28	-92.3	1.46
Raton Basin, CO	1	37.16	-104.8	37.13	-104.75	5.09
	2	37.1	-104.62	37.13	-104.75	12.39
	3	37.12	-104.68	37.13	-104.75	6.67
	4	37.2	-104.67	37.13	-104.75	10.46
	5	37.13	-104.7	37.13	-104.75	4.74

Paradox Valley, CO	1	38.3	-108.9	38.3	-108.9	0
Youngstown, OH	1	41.135	-80.69	41.1275	-80.686	0.89
	2	41.12	-80.682	41.1275	-80.686	0.89
Ashtabula, OH	1	41.545	-80.441	41.545	-80.441	0
Azle, TX	1	32.98	-97.58	32.99	-97.565	1.79
	2	33	-97.55	32.99	-97.565	1.79
Dallas/FTW, TX	1	32.85	-97.05	32.85	-97.05	0
Timpson, TX	1	31.85	-94.47	31.87	-94.45	2.31
	2	31.88	-94.43	31.87	-94.45	2.31

The earthquake locations were retrieved from the Advanced National Seismic System (ANSS) Comprehensive Catalogue (ComCat), which is an earthquake database available for public use through the USGS. Accuracy of the spatial parameters is approximately 1.8 km (1 mile). Parameters for the earthquake search included: (1) all earthquake occurrences within a 100 km (62 miles) radius of identified injection well locations, (2) an initial injection start date as provided within the literature (Table 4.3), (3) a final occurrence date of December 31, 2015, (4) depth was not specified, and (5) a moment magnitude of 2.5 or greater, as this magnitude is considered the magnitude at which the earthquake is commonly felt at the surface (although in some areas, attenuation is limited and they are felt at smaller magnitudes; Gutenberg & Richter, 1942). Earthquake occurrences cited in the literature were not used due to the diverse approaches to generating the respective earthquake catalogs. Each investigation used different types of seismic stations and methods for recording earthquake occurrences, resulting in inconsistencies across research locations. The USGS data provides a uniform catalog of earthquake occurrence data appropriate for this systematic approach. As the dominant requirement for this analysis is the spatial location of the felt earthquakes, a loss of small earthquakes or uncertainty about the depth of the hypocenters does not affect this analysis.

Table 4.3

Cumulative Distance Curve Results for Felt Earthquake Occurrences Away from Injection Well Locations

PISA	Number of Eq. Events	Radius from well (km)	Nearest Event (km)	10% are within (km)	50% are within (km)	90% are within (km)	R^2 Log Trend	Initial Injection Date
Brewton	7	100	6	7.3	17	72.8	0.86	1/1/75
Guy-Greenbriar	248	100	1.24	2.99	6	21.2	0.89	4/15/09
Raton Basin	260	100	1.5	9.3	20.2	33.9	0.85	7/1/97
Paradox Valley	17	70	1.3	3.76	7.2	71	0.77	7/11/91
Youngstown	8	90	0.63	0.84	2	92	0.90	12/29/10
Ashtabula	14	30	1.14	1.14	4	28	0.94	1/1/86
Azle	25	46	2	5.75	9	21	0.79	6/1/09
Dallas/Ft. Worth	53	44	2.7	9.32	13	39	0.73	11/12/08
Timpson	13	100	4	4.46	8	43	0.85	1/1/06
Composite	-	-	2.3	4.98	9.8	47.4	0.89	-

Once the locations of the earthquakes were found, the Haversine equation was used to calculate the distance between earthquake and central well location (Schumaker & Sinnott, 1984). The Haversine equation is used for creating distances between two points on the earth by their latitude and longitude, and is calculated as:

$$D = Rc \tag{5}$$

where D is the distance between two points on a sphere (m) and *R* is the earth's radius (mean radius = 6,371 km). *C* is calculated as:

$$\Delta lat = lat_2 - lat_1 \ , \ \ \Delta long = long_2 - long_1 \tag{6}$$

$$a = sin^2\left(\frac{\Delta lat}{2}\right) + cos(lat_1)\,cos\,(lat_2) sin^2\left(\frac{\Delta long}{2}\right),$$

$$c = 2atan2\left(\sqrt{a}, \sqrt{(1-a)}\right), \ c = 2atan2\left(\sqrt{a}, \sqrt{(1-a)}\right)$$

The data were treated similarly to the mathematical and graphical depictions of landslide occurrences after an earthquake in the area of Santa Cruz, California. Keefer (2000) used concentration of landslide occurrences to determine if spatial patterns exist between landslides and an earthquake epicenter. Similarly, this research investigates potential spatial relationships between earthquake occurrence and injection disposal well locations. The earthquakes were ranked by the distance of occurrence from closest to furthest from injection well locations. In some instances, two PISAs were located within the same 100 km (62 miles) radius used for identifying earthquake locations. Patterns within the data sets identified distances where earthquakes had ceased, then began to increase when approaching the nearby PISA. The radius was then shortened to this identifiable radius to limit the interference from neighboring PISAs. The concentration of earthquake occurrences was found by calculating the percentile of each occurrence per total number of earthquakes for each site. The percentile for each earthquake occurrence was calculated for each earthquake to accommodate the variation in the number of earthquakes between the data sets. The percentile of events over distance was plotted to find cumulative distance curves. Once the cumulative distance curves were established, a logarithmic trend line representing the hydraulic trend found in the Thiem type curves was applied to the data sets at each PISA to examine mathematical relationships among the data.

Geometric analysis. If the pressure differential generated by injection wells induces seismic activity, then understanding pressure decay laterally from injection wells should provide a pattern capable of predicting the distance from an injection well where a felt earthquake is more likely to occur. To investigate the lateral decay rate, the data were evaluated relative to steady state well hydraulics for injection wells as a Thiem analysis (Thiem, 1906).

Evaluating a simple Thiem well solution:

$$h_0 - h = \frac{Q}{2\pi T} \ln\left(\frac{R}{r}\right) \tag{4}$$

Where h_0 and h are head levels, T is Transmissivity, Q is injection rate, R is the external radius of influence, and r is the radius from the injection well to the initial distance of interest (Thiem, 1906). If a pressure pulse generated by the injection well is sufficient to generate seismicity, the distribution of earthquakes with distance may follow the distribution of pressure changes generated by the well. In this case, the change from the well is the important factor in understanding how the pressure distance is influenced. On a relative basis for the well, the discharge and the transmissivity of the formation do not influence the decay rate of the pressure pulse as a percentage of the initial pressure at the well. Therefore, the problem becomes a geometric one of logarithmic pressure decay as a percentage of the pressure near the well (Figure 4.1). The model becomes a simple two-parameter model: One parameter is the initial distance the wellhead pressure influences to generate seismicity (r) and the second is the radius of influence of the injection well (R).

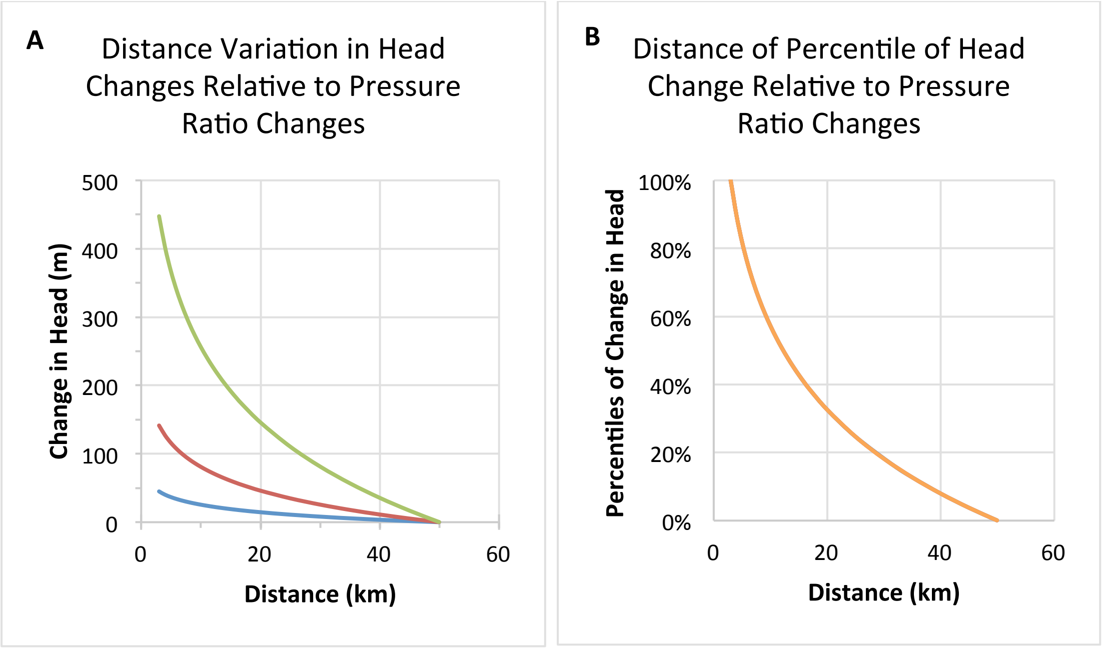

Figure 4.1: A. Curves represent an order of magnitude difference on a logarithmic scale (Q/T ratio is 10 for blue line, 316 for red line, and 1000 for green line), which addresses the range of Q/T ratios from the nine PISAs. B. When change in head is expressed as percentiles, each line collapses into the same decay curve, demonstrating the dependence on only geometric parameters instead of hydraulic parameters.

The log trend line equation of the model was used to calculate the geometric distance values (r and R) for each of the nine PISAs (Appendix D). The log trend equation is:

$$y = m \ln x + b \tag{7}$$

where y is the proximal pressure pulse, x is the radius of influence (R), m is the slope of the trend and b is the y-intercept. The values of m and b provided from the log trend in each analysis were used to calculate the pressure pulse (r) and radius of influence.

For this work, the field data are compared to solutions of equivalent radius of influence of 100 km (62 miles) as a boundary to the problem. The initial radius of well head pressure is adjusted to determine the 10th and 90th percentile of pressure dissipation and the median distance for the initial radius. These are compared against the available field data.

The inverse problem is also performed. Each field case has a best field logarithmic model generated to find a best-fit parameter for initial radius and radius of influence. The parameters are compared across the available field cases to evaluate 1) the utility of the simple hydraulic model and 2) the stability of the model across a range of field cases.

Sensitivity analysis. A sensitivity analysis can indicate to which conditions systems are most sensitive (Mercer & Faust, 1980). A sensitivity analyses was incorporated into this research to discover how key parameters influence the results. Running averages of the data were created to isolate effects of certain parameters by adding one location at a time into the calculation until all locations were included. There were three parameters of influence isolated through this sensitivity analysis: (1) number of felt earthquakes, (2) duration of seismic activity, and (3) hydraulic parameters. Each analysis ranked the data from lowest to highest values. For example, the first analysis for number of felt earthquakes ranked the nine PISAs from smallest to largest, with Brewton being first with seven felt events and Raton Basin last with 260 felt events. Then, the running averages of distances in the 10th, 50th, and 90th percentiles were calculated in the order each location was ranked (i.e. Brewton, then Youngstown was averaged with Brewton, then Timpson was added to the Brewton and Youngstown average, etc.). The running averages address the variability within the data sets, and determines how each parameter affects the composite. The chosen percentiles were selected to determine patterns among the proximal earthquake events (10th), the median value for amount of events (50th), and the majority of events (90th). This process was repeated for the duration of seismicity and hydraulic pressure ratio (Q/T) analyses. The averages were plotted to analyze trends among the data sets to see how the number of earthquakes, duration of seismicity, and hydraulic parameters impacted distance from injection disposal wells. The time in years for each event in each location was found by subtracting the difference between initial injection and first earthquake occurrence. Injection rate (Q) and transmissivity (T) are parameters within the Thiem equation representing the hydrogeologic relationship among the data. By assuming the distance is affected by hydrogeology, the pressure ratio (Q/T) can be calculated to obtain an expected event distance for each location. Six of the nine PISAs used for this research provided average injection rates within the literature and were used for the pressure ratio (Q/T) analysis.

Results

The nine PISAs with complete sets of data provided similar patterns for seismicity relative to distance from the injection well locations. Earthquake events clustered near, but not at, the injection disposal well. The number of events declined as distance from the well increased. Most locations had some offset distance for the majority of the adjacent felt seismicity. The Guy-Greenbrier PISA provides an example of earthquake occurrences versus distance from injection wells plotted as earthquake distance against percentage of felt earthquakes (Figure 4.2) (all nine PISA analyses provided in Appendix D).

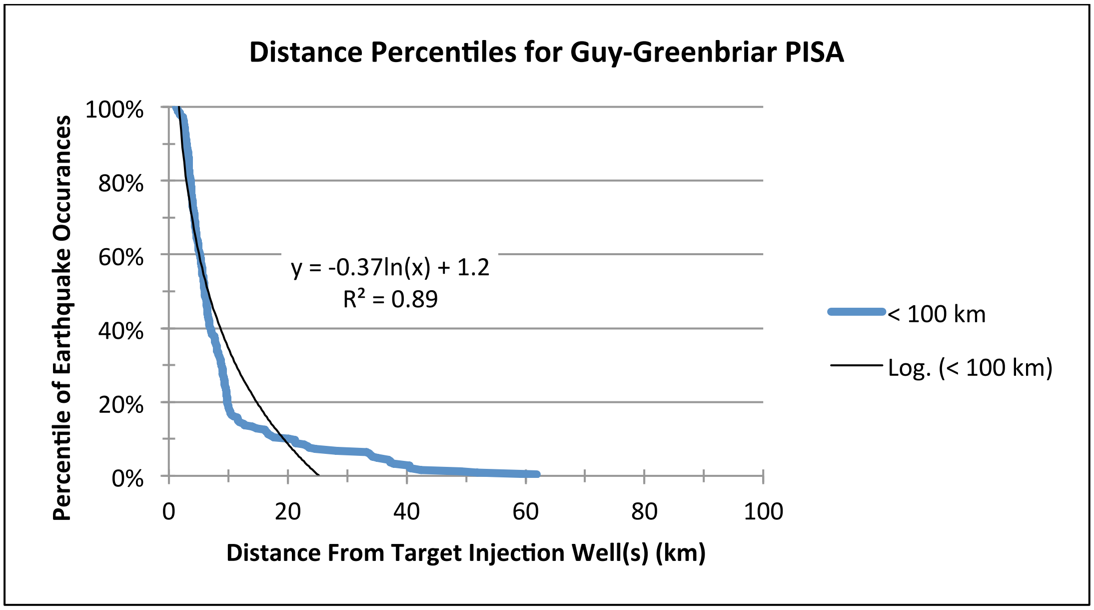

Figure 4.2. Percentiles of felt earthquake occurrences within 100 km (62 miles) of targeted injection well in the Guy-Greenbriar PISA in Arkansas. Blue line represents the Guy-Greenbriar percentiles and black line is the log trend fitting the data with an r^2 of 0.89.

Five locations (Paradox Valley, Azle, Dallas/Ft. Worth, Youngstown, and Ashtabula) showed results indicating a nearby increase in seismicity, at a noticeable distance away from the well. To adjust for the close proximity areas, the radius for Azle, Dallas/Ft. Worth, Ashtabula, and Youngstown areas were reduced. The bounding radius for each evaluated site is denoted in Table 4.3.

A logarithmic trend line (corresponding to the logarithmic decay rate demonstrated by the Thiem analysis) fit the data sets within each location with r^2 values ranging from 0.73 to 0.94, accounting for the majority of variability within the models. This trend indicates earthquake occurrences are predominately in proximity to the injection well, with a decrease in earthquakes distal from the well at a rate described by a logarithmic decay. The logarithmic function varied from slopes of -0.5 to -0.16 and intercepts of 0.8 to 1.9 in values between the sites (Table 4.4).

Table 4.4
Thiem Solution Results From Logarithmic Distance Trends of 9 PISAs

PISA	Slope (m)	Y-Intercept (b)	Radius of Influence (R)	Pulse Radius (r)
Brewton	-0.31	1.38	90.0	3.42
Guy-Greenbriar	-0.37	1.21	25.2	1.74
Raton Basin	-0.47	1.9	54.1	6.57
Paradox Valley	-0.31	1.1	35.9	1.4
Youngstown	-0.16	0.8	129.7	0.29
Ashtabula	-0.24	0.88	41.5	0.61
Azle	-0.45	1.47	26.3	2.83
Dallas/Ft. Worth	-0.5	1.82	39.5	5.24
Timpson	-0.42	1.43	30.1	2.8
Composite	-0.35	1.36	48.8	2.8

The closest felt earthquakes occurred between 0.63 and 6 km (3.7 miles) from the injection locations, with an average nearest distance of 2.0 km (1 mile). The 90th percentile distance, or 10% of earthquake occurrences ranged from 0.84 to 9.32 km (0.5 to 6 miles) with an average distance of 5 km (3 miles). The range of median distances for the dataset is between 2 and 20 km (1 and 12 miles), with an average of 9.8 km (6.1 miles). Ninety percent of earthquakes occurred within 21 to 72 km (13 to 45 miles) with an average of 47.4 km (29.4 miles) from injection locations. The individual trends for the nine locations are provided in Table 4.3.

The results from the geometric analysis indicate similar results to the composite of the cumulative distance curves. The pulse diameter (r) ranged from 0.28 to 6.5 km (0.17 to 4 miles) with a composite average of 2.8 km (1.7 miles). The radius of influence ranged from 25 to 130 km (15.5 to 81 miles) with an average of 48.8 km (30.3 miles). A compilation of cumulative distance curves, composite curve, and distance curve resulting from the Thiem analysis are shown in Figure 4.3.

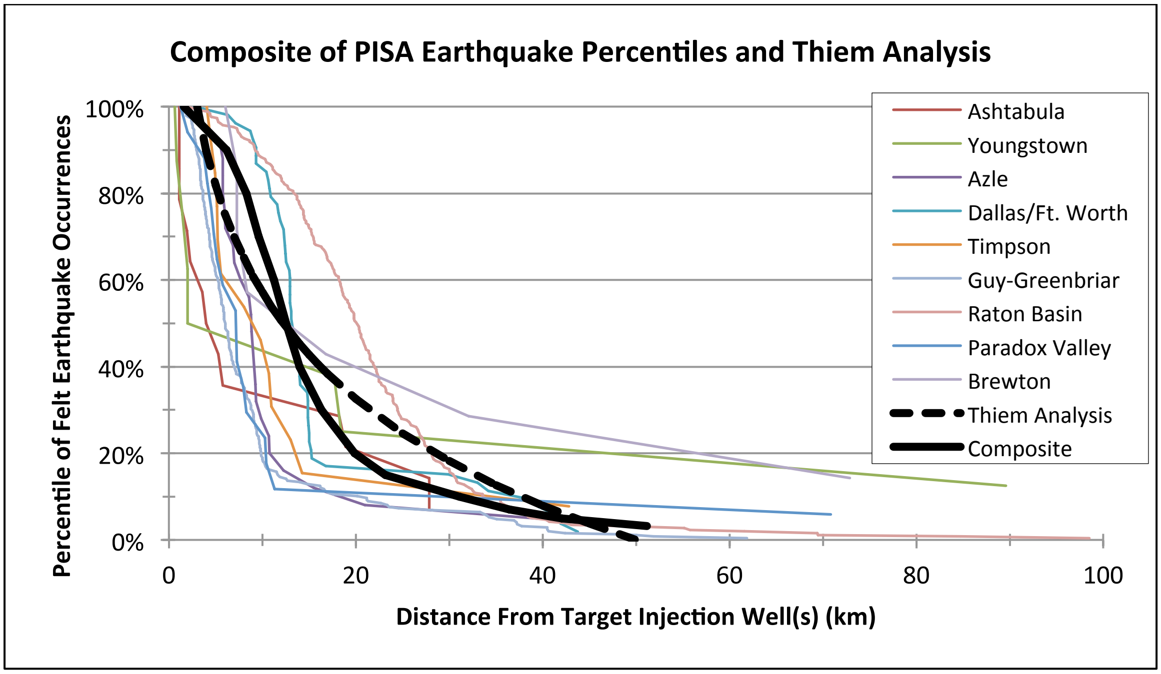

Figure 4.3. Compilation of all nine PISA percentile curves with composite and Thiem analysis included.

The sensitivity analyses isolating parameters to identify any influence provided identical distance averages to the composite cumulative distance curve, since the running average and composite average use the same distance values. The Q/T ratio running average differs slightly, as only six of the nine locations were viable for Q/T ratio sensitivity analysis. When ranked by number of seismic events, there is a steady average for the 10th and 50th percentiles, with a distance decreasing in the 90th percentile (Figure 4.4). When ranked by duration of seismicity (which also corresponds to duration of injection), the 90th percentile average shows no clear pattern, while the 10th and 50th percentile range distances increase slightly (Figure 4.5). When ranked by Q/T ratio, the 10th, 50th, and 90th percentile averages all show an increase in distance as the Q/T ratio is increased (Figure 4.6).

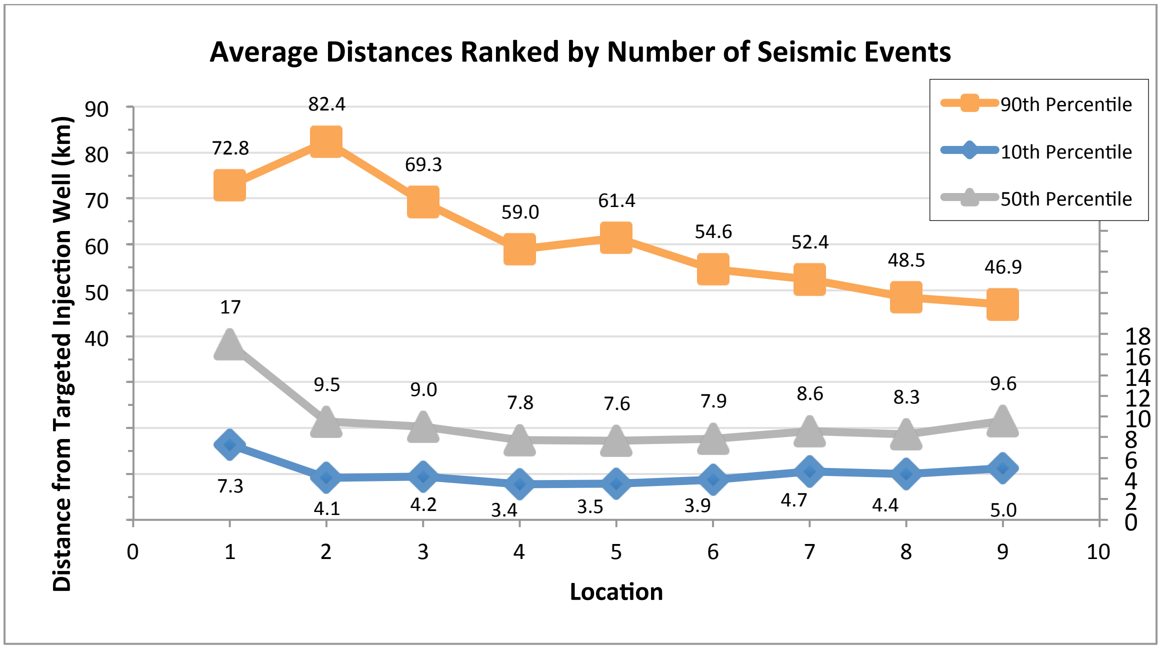

Figure 4.4. Sensitivity analysis displaying results for 10th, 50th, and 90th percentile running averages ranked by number of seismic events for nine PISAs.

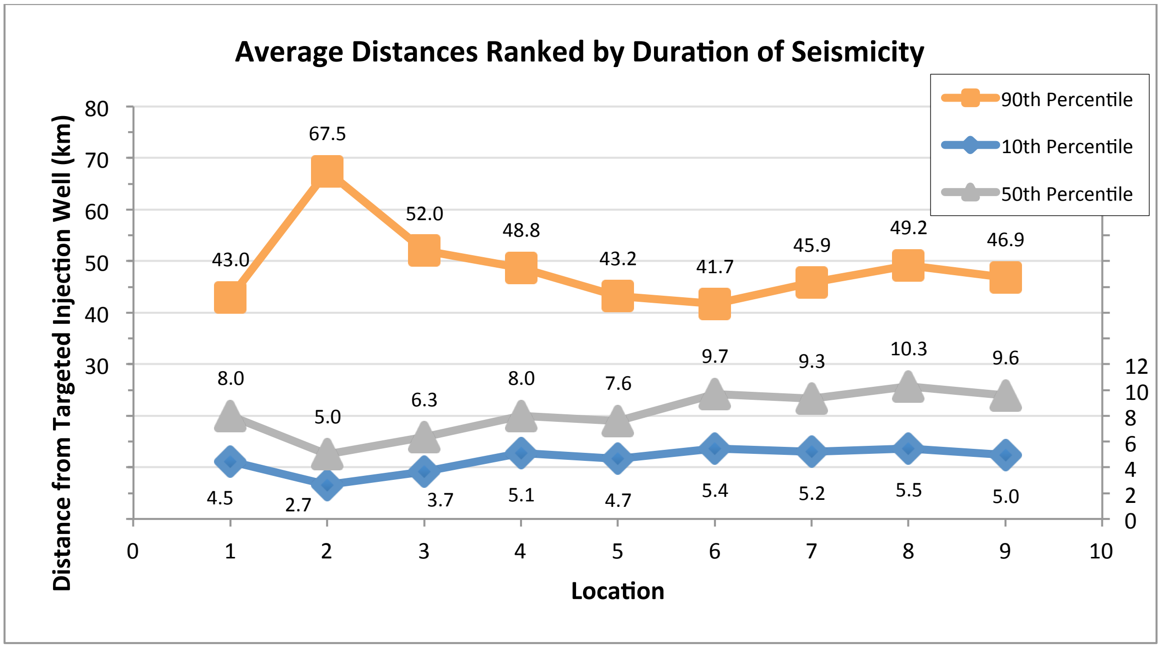

Figure 4.5. Sensitivity analysis displaying results for 10th, 50th, and 90th percentile running averages ranked by duration of seismicity for nine PISAs.

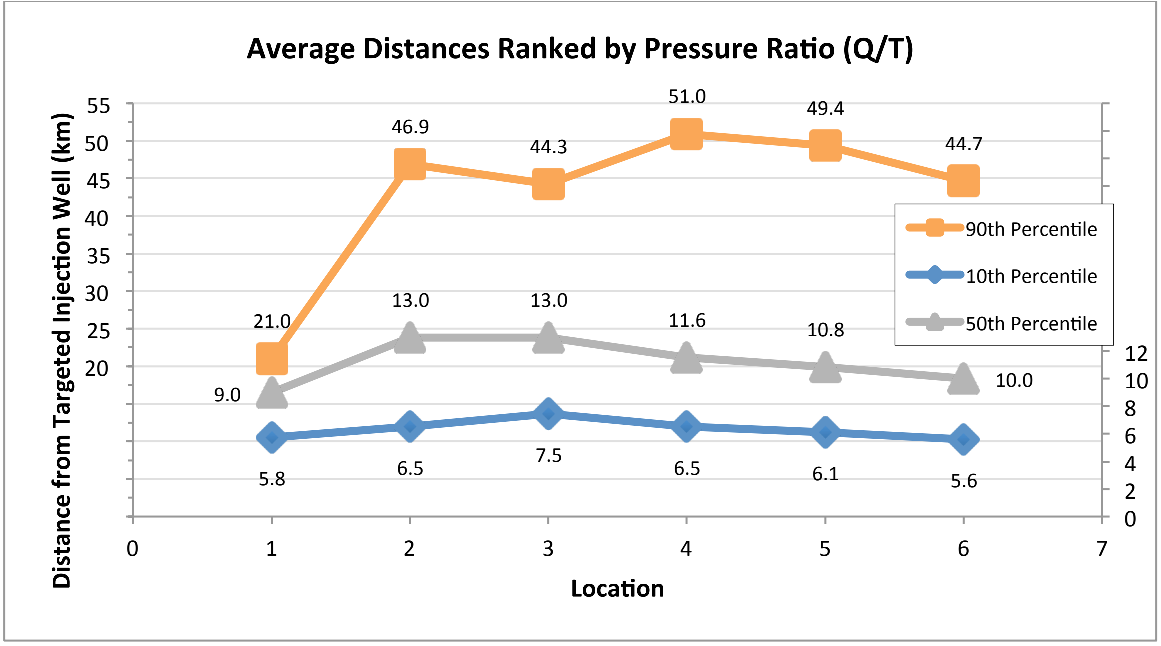

Figure 4.6. Sensitivity analysis displaying results for 10th, 50th, and 90th percentile running averages ranked by Q/T ratio for nine PISAs.

The cumulative results from all analyses indicate an initial pressure pulse radius, or nearest seismic event radius to be between 2 km (1 mile) from the injection wells used in this research. Additionally, to account for the majority of felt earthquake events, or 90%

of events, the pressure radius is within 47.4 km (29.5 miles) of these injection disposal wells.

Discussion

This investigation reveals consistent patterns among PISAs, identifying radial distances from injection disposal wells where felt earthquakes are most likely to occur. Fifty percent of seismicity may be limited to a 10 km (6.2 miles) radius, but to ensure 90% of seismicity is addressed, a radius of 47 km (29 miles) should be investigated. This has implications for regulatory agencies attempting to monitor injection disposal well activity and for industry searching for viable locations for creating injection locations. The log decay of distances fits the log decay of hydraulics, implying that a resulting pattern of pressure changes will be related to the distance from injection well. This does not imply which direction the distance will be or that the flow is purely radial.

In locations where a reduction in earthquakes occurred due to a hiatus in injection, state regulatory agencies in areas such as Colorado, Ohio, and Arkansas simply ceased injection operations. For these locations, it was apparent which well was correlated with increased seismic activity. As mentioned previously, Oklahoma has hundreds of Class II injection wells, making it difficult to isolate specific wells responsible for the increase in earthquake activity (Murray, 2015). The Oklahoma Corporation Commission (OCC) has issued a traffic light system, where all disposal wells are monitored daily and regulated based on the threat of seismicity in the area of injection (OCC, 2016c). The OCC has maintained volume limits, consistent bottomhole pressure readings, and evaluating if wells are in contact or communicating with basement rock. Current wells located within 5 km (3 miles) of a critically stressed fault and within 10 km (6.2 miles) of an earthquake swarm will warrant a technical meeting with the operator and the OCC (Baker, 2015). This research indicates a radial distance of at least 48 km (30 miles) from critically stressed faults in order to address the majority of felt earthquakes occurring due to injection.

This research indicates a distance of 2.0 km (1 mile) where earthquakes initially occur, on average, across locations. This means injection disposal wells are unlikely to be directly above felt earthquake hypocenters. Since the majority of seismic activity occurs at faults, it is likely the injection well locations in this study are located an average distance of 2.0 km (1 mile) from critically stressed faults. This research only considers felt seismicity at magnitudes of 2.5 or greater. It is possible this initial distance of seismic events would differ if smaller magnitude seismicity were included. Additionally, it is important to emphasize this distance is an average. One should not assume an initial seismic distance of 2.0 km (1 mile) from injection wells when injecting directly above critically stressed fault.

The sensitivity analysis allowed for influential parameters to become more apparent. As sites increase in number of events, the maximum average distance decreases. Earthquake events appear to accumulate proximal to the central well location as the number of earthquakes increases. This can be explained by a continuing increase in pressure proximal to injection wells as injection continues. An increasing trend in the data ranked by the Q/T ratio and duration of seismicity indicates as injection increases within a transmissive system, the distance earthquakes are expected to occur increases over time. This corresponds to the Kaiser Effect (Baisch & Harjes, 2003; Baisch et al., 2010).

Some locations have established the existence of historical seismicity within the area. This research does not delineate between induced seismic activity and historical seismicity. The origins of the earthquakes are not specified by the USGS. If all of the seismic events were natural in origin, there is unlikely to be a strong correlation between distances from injection wells and logarithmic decay with distance consistent with pressure decay from wells. This research does not address depth of earthquake hypocenters and depth distance from injection wells. Currently, researchers have identified earthquakes can occur at least 4.0 km (2.5 miles) from the depth of injection (Healy et al., 1968; Hsieh & Bredehoeft, 1981). Additional research prompted by this study includes (1) evaluating patterns of earthquake magnitudes as distance increases from the well location, (2) identifying patterns in the areas of Cogdell, Fashing, and Central Oklahoma where well interaction may be significant, and (3) identifying and investigating areas where the Q/T ratio is high but seismic activity is low or nonexistent.

The results of this work do not replace the need for site characterization prior to well establishment in order to determine the viability of a location for subsurface injection. Areas such as Central Oklahoma maintaining hundreds of active injection wells or the Guy-Greenbriar PISA where injection wells were hydraulically connected to a critically stressed fault are examples of locations where site-specific data sets are crucial to establishing pre-existing conditions. The expected distances of earthquake occurrences found through this research may change in light of site-specific data sets, with different earthquake catalogs or geologic boundary conditions (Horton, 2012). Due to the active induced seismic hazard with the CEUS, this research presents the overall trends between

PISAs in order to provide a systematic hydrogeologic approach by which estimates can be generated.

CHAPTER V

PRESSURE MIGRATION PREDICTIONS IN AREAS OF POTENTIALLY INDUCED SEISMICITY

Article Submission: Potential journals for submission include *Groundwater* and *AAPG Environmental Geoscience*

Authors: Caitlin Barnes and Todd Halihan

Abstract: Industrial waste water injected into disposal wells can cross critically stressed faults in the subsurface and induce seismicity. The rate at which this fluid moves through the injection interval, or rate of migration, is dependent on the rate of injection and the hydrogeologic properties of the injection interval and adjacent formations. This research systematically reviews 17 USGS identified potentially induced seismic areas to test if pressure migrations estimates are possible given the currently available data in these locations. Site-specific hydrogeological data in these areas are not prevalently available. A compilation of injection rate values found through state and federal agency data were used to evaluate hydrogeological relationships associated with injection rate and earthquake occurrences. Strong correlations exist between estimated pressure ratio generated at the well and felt earthquake occurrences, providing analytical models for assessing potential seismic hazard. No correlation was found between injection rate and injection interval transmissivities, suggesting a lack of uniform site characterization and injection design based on well hydraulics prior to onset of injection. This research illustrates the need for regional hydrogeologic evaluations in order to assess potential seismic hazards and determining appropriate rates of fluid injection.

Keywords: induced seismicity, hydrogeology, pressure migration, subsurface injection

Introduction

It is possible to induce seismicity by injecting fluids into subsurface injection disposal wells (Ellsworth, 2013; Healy et al., 1968; Raleigh et al., 1976; Simpson, 1986). In early 2015, the USGS identified over 17 locations across the Central and Eastern United States (CEUS) at risk for fluid injection induced seismicity (Peterson et al., 2015). The focus of the USGS is on the associated seismic hazard from these potentially induced seismic areas (PISAs) rather than determining the cause of increased seismicity. If the origin of seismicity is anthropogenic, it is critical to establish the cause to address or reduce the associated hazard within each PISA.

Within the PISAs, it is important to ensure the location is not affected by natural seismicity. Researchers may accomplish this by correlating injection activity to the onset of seismic activity changes as an indicator of potential seismic hazard. For example, earthquakes in Ohio clustered on a fault in close proximity to an injection well. These earthquake occurrences correlated to daily injection volume and rate. When injection was reduced or ceased, there was a direct correlation to a reduction in seismicity (Kim, 2013). Similarly, there was a reduction in formation pressure and earthquake occurrences near the Guy-Greenbriar fault in Arkansas after an emergency shut down of injection wells (Horton, 2012). In an injection experiment in Rangely, Colorado, researchers first obtained subsurface pressures and modeled those pressures throughout a designated injected area. Once injection began, they verified the fluid pressure distribution model matched physically obtained pressure measurements (Raleigh et al., 1976). The earthquakes at Rangely were turned off and on by injecting and then returning fluids to the surface, thus confirming induced seismicity beyond a reasonable doubt.

There are several factors that must be in place to induce seismicity through fluid injection such as fault orientations, locations, stress load, and baseline pressure of the injected formation (Zoback, 2012). Other considerations such as rate of injection (Weingarten et al., 2015) and proximately to basement (Kim, 2013; Zhang et al., 2013) are also essential to induced seismicity analyses. However, the inherent mechanism of fluid injection induced seismicity is subsurface pressure migration originating from an injection disposal well (Healy et al, 1968; Hsieh & Bredehoeft, 1981; Raleigh et al., 1976). Within the CEUS, the crust is at or near the strength limit due to high shear stress (Peterson et al., 2014; Townend & Zoback, 2000). Any pressure changes applied to faults within these critically stressed regions could trigger an earthquake (McGarr et al., 2002; Nicholson & Wesson, 1990; Peterson et al., 2014). This implies an understanding of subsurface pressure migration is needed in order to address hazards of induced seismicity. Unfortunately, there is a substantial lack of associated hydrogeological data in PISAs within the CEUS (Barnes & Halihan, in review; Gomberg & Wolf, 1999; Keranen et al., 2013; McGarr, 2015; Sanford et al., 2006;).

Hydrogeology

Pressure may continue to migrate through the subsurface after injection ceases, unless a period of backflow is implemented at the well (Healy et al., 1968; Raleigh et al., 1976). Earthquakes at Rocky Mountain Arsenal (RMA) continued to occur years after injection ceased (Healy et al., 1968). If earthquakes continue in this manner, it is logical to assume earthquakes could continue to occur even if all wells were shut down simultaneously within a location. Knowing the hydrogeology within these locations may provide a more accurate understanding of pressure migration, which would assist in hazard predictions. Additional regional or site-specific hydrogeologic data are necessary to make predictions based on subsurface pressure migration theory. However, the lack of available hydrogeologic data within current research efforts necessitates the use of analytical solutions or models to make general predictions of pressure migration within these PISAs.

The Theis equation is an analytical model of pressure migration, which can be used to make pressure migration estimations in areas of potential fluid induced seismicity (Hsieh & Bredehoeft, 1981). The same equation can be used to calculate fluid buildup, which is how pressure migration predictions may be obtained. The Theis equation is used for transient flow conditions associated with short-term or temporary injection analyses. The 17 PISAs identified by the USGS experienced or are currently experiencing injection for a year or more, allowing ample time for the system to reach steady state flow conditions. For steady state, the appropriate analytical model becomes the Thiem equation. The required parameters needed to implement the Thiem equation include transmissivity (hydraulic conductivity and interval thickness), fluid injection rate, and the geometric radius for proximal and distal flow boundaries. The ratio of injection rate to transmissivity accounts for the hydraulic parameters within the Thiem equation and is directly proportional to the subsurface pressure differential. A Thiem analysis combined with accurate bottomhole pressure measurements are basic parameters for determining a realistic injection rate a system can consume without increasing the subsurface pressure beyond a seismically critical point.

Injection rates and volumes are readily available in the literature, since these parameters are typically monitored by state regulatory agencies (Barnes & Halihan, in review). Transmissivity can be obtained through hydraulic tests in injection wells. In the absence of hydraulic testing, transmissivity can be found through the product of hydraulic conductivity and injection interval thickness. Thickness values are somewhat available, with most literature providing injection depth ranges (Barnes & Halihan, in review).

Transmissivity of an injection interval depends on the intrinsic permeability of the rock formation fractures and fluid properties such as viscosity and density. Baseline pressure of the injection interval is important in determining whether the system is initially overpressured or underpressured. It is critical to capture baseline pressure, as pressure changes within underpressured systems have been known to generate seismicity (Rubinstein et al., 2014). This knowledge provides insight as to how much pressure the system can withstand and maintain stability. Once pressure conditions are established, obtaining consistent bottomhole pressure measurements during injection is critical for quantifying the system response to pressure. Aquifer tests at injection well locations and throughout the injected formation are recommended to capture transmissivity and pressure values necessary to make flow or pressure migration predictions.

Davis and Pennington (1989) argue that bottomhole pressure measurements are useful, but are not particularly beneficial in isolation. To gain an understanding of the whole system, pressure measurements should be obtained throughout the injected formation (Davis & Pennington, 1989). Similarly, permeability data can change by orders of magnitude due to the heterogeneity of formations, by amount of fractures within the system, and by the scale of the measurement (Galvao et al., 2016; Halihan, 1999; Kiraly, 1975). This phenomenon of permeability changing with measurement type is called the permeability scale effect. It is estimated permeability values could change by nine orders of magnitude in a single formation due to well scale effects (Halihan, 2000). It is important to obtain these values from within the injection interval itself (bottomhole) and not through core samples, which only provides matrix permeability. Measurements should be taken not only at the injection interval, but also in adjacent formations where flow may migrate.

Pressure Migration

Fluids injected into injection disposal wells increases the pore pressure within the formation, which decreases rock strength near faults. It is not necessary for the fluid itself to reach the fault in order to increase the pressure at fault lines (Mulargia & Bizzarri, 2014). Changes in pressure within the formation as the fluid pushes into the system can also trigger earthquakes. Preferential pathways can increase the rate at which pressure or fluid moves through the system. These fluid pathways, such as fractures and faults, provide conduits for fluid and pressure to move from one subsurface lithology into another (Zhang et al., 2013). Knowing the lithology and geological features of the injection interval will assist predictions of pressure migration. Table 5.1 lists injection interval descriptions for each of the 17 PISAs.

Table 5.1
Injection Interval Descriptions for the 17 USGS Identified PISAs

USGS PISA	Injection Interval	Lithology	Thickness (m)	Reference
Brewton, AL	Tuscaloosa Group	Sandstone/shale	243	Gomberg & Wolf (1999)
Guy-GreenBriar, AR	Ozark Aquifer	limestone/dolomite (overlies basement)	~965	Horton (2012)
RMA, CO	Basement	crystalline rock	Not available	Evans (1966); Healy et al. (1968); Hsieh & Bredehoeft (1981)
Raton Basin CO/NM	Dakota Formation	conglomeritic sandstone (overlies basement)	~850	Meremonte et al. (2001)*; Rubinstein et al. (2014)
Rangely, CO	Webber Sandstone & Basement	Sandstone and crystalline rock	408	Gibbs et al. (1972); Raleigh et al. (1976)

Greeley, CO	Fountain Formation	conglomeritic sandstone (overlies basement)	~244	Yeck et al. (2014)*
Paradox Valley, CO	Leadville Limestone	limestone (overlies basement)	127	Ake et al. (2005); Block et al. (2014)
Dagger Draw, NM	Ellenberger Formation	dolomite (overlies basement)	~760	Sanford et al. (2006); Pursley et al. (2013); Herzog (2014)
Youngstown, OH	Mt. Simon & Basement	sandstone & crystalline rock	~298	Kim (2013)
Ashtabula, OH	Mount Simon Sandstone	sandstone & crystalline rock		Seeber et al. (2004)
Central OK	Arbuckle Group	carbonates	1300	Keranen et al. (2013); Keranen et al. (2014)
North OK/South KS	Mississippi Limestone	limestone	~350-1100	Rubinstein et al. (2014)*; Gobel (2015); McNamara et al. (2015)
Azle, TX	Ellenberger Formation	dolomite (overlies basement)	~760	DeShon et al. (2014)*; Hornbach et al. (2015)
Fashing, TX	Canyon Reef Limestone	limestone	100	Pennington et al. (1986); Davis et al. (1995); Frohlich & Brunt (2013)
Cogdell, TX	Ellenberger Formation	dolomite (overlies basement)	45	Davis & Pennington (1989); Gan & Frohlich (2013)
Dallas/FTW, TX	Edwards Limestone	limestone	760	Frohlich et al. (2010); Frohlich et al. (2011); Frohlich (2012)
Timpson, TX	Rodessa of the Trinity Formation	limestone	~98	Brown & Frohlich (2013)*; Frohlich et al. (2014)

Injection within the 11 of the 17 PISAs occurred in carbonate rock. Permeability within carbonate rock is heterogeneous and anisotropic due to the formation being fractured and often karstic (Mangin, 1975). Patterns among earthquake hypocenters can often identify critically stressed faults, such as the Guy-Greenbriar fault in Arkansas (Kim, 2013), the Wilzetta Fault in Oklahoma (Keranen et al., 2013), and the Mt. Enterprise fault zone in Texas (Frohlich et al., 2014). These faults intersect the injection intervals at each location and are often connected to crystalline basement faults. In Ashtabula, Ohio, industrial fluids were disposed in the Mt. Simon Sandstone, which is a highly fractured sandstone directly overlaying basement rock as evidenced through core samples (ODNR, 2016). Horton (2012) explained fluid injected into sedimentary rock in Arkansas had a direct fluid pathway to the Precambrian basement through the Guy-Greenbriar fault. Three of the USGS identified PISAs inject into the Ellenberger Formation, which also lies directly above Precambrian basement. In Rangely and Rocky Mountain Arsenal, fluids were injected directly into crystalline basement (Healy et al., 1968; Raleigh et al., 1976). Deep boreholes in Colorado suggest the basement is critically stressed (Nicholson et al. 1988). Due to the high correlation between fluid injection reaching crystalline basement and the occurrence of earthquakes, Zhang et al. (2013) recommend areas where there is no sedimentary basal seal to prevent fluids from travelling into the basement should not be used for fluid injection. This has significant implications for locations such as Oklahoma where the major injection interval is the Arbuckle group, which appears to have direct hydraulic connection to the basement formations in seismic data (Carr, McGovern, Gogel, Doveton, 1986).

Injection interval information provided in the literature indicates a consistent pattern of injecting into fractured lithologies often containing fluid and pressure pathways directly into crystalline basement rock. If the fracture properties were known, the hydraulic properties of the formation could be calculated. Since locations and/or sizes of the fractures within the system are unknown, the formation as a whole can be classified as a fractured rock system. Additionally, hydraulic data can be evaluated with expectations that fracture flow is the general means for propagating pressure waves away from the well. The range of flow patterns in fracture rock formations make fluid migration predictions difficult without site-specific hydrogeologic data (Cook, 1993). In the absence of available data, it becomes necessary to analytically evaluate hydrogeologic data within PISAs to address the seismic hazard within the CEUS. The purpose of this research is to determine if pressure migration estimations can be made using existing hydrogeologic data within the 17 PISAs and supplementing the missing information with known site-specific hydrogeologic characteristics.

Methods

The investigation included a systematic review of the 17 USGS identified PISAs gathering available data for the following data sets: injection interval thickness and lithology, transmissivity, permeability, hydraulic conductivity, storativity, formation pressure measurements, injection rates, injection volumes, and the identification of injection disposal wells suspected to be potential sources for injection induced seismicity. Table 5.1 shows the injection intervals and corresponding formation thicknesses for each PISA, with the list of peer-reviewed literature from which the data were collected. Data for transmissivity and injection rates are provided in Table 5.2, as well as the Q/T ratio (injection rate/transmissivity, pressure ratio [m]) between these values used for estimating relative pressure differentials potentially generated in the injected interval. Estimated values for injection interval thickness and transmissivity were found through state or federal geological archives for the lithologies (Table 5.1). The Northern Oklahoma and Southern Kansas PISA was removed from this analysis, as specified injection wells (and injection rates) contributing to induced seismicity were not identified within the existing literature.

Each PISA identified an injection well or group of injection wells, which may have contributed to an increase in seismic activity. Once the coordinates for the identified injection wells were known, earthquake occurrences within a 100 km (62 miles) radius were collected from the USGS public earthquake database called the Advanced National Seismic System (ANSS) Comprehensive Catalogue (ComCat). Earthquake occurrences were used in a seismic analysis, which compared seismic activity to pressure migration estimations. Central Oklahoma, Cogdell, Texas, and Fashing, Texas were not included in seismic analyses as magnitude and scale of injection within these locations are too extensive to readily isolate injection wells likely associated with seismicity. Rangely, Colorado and Northern Oklahoma and Southern Kansas PISAs were removed from the seismic analysis due to incomplete data regarding injection well locations. The felt earthquake data were retrieved from the USGS earthquake database, using the following parameters: (1) earthquakes occurring within 100 (62 miles) of injection disposal well location, (2) beginning from the initial injection date provided in the literature for specified wells until December 31st, 2015, and (3) earthquake magnitude 2.5 or larger. The database records began in 1973, which is after the earthquake events at Rocky Mountain Arsenal (RMA) occurred. However, the literature for RMA remains one of the best research investigations from a hydrogeologic perspective of all of the PISAs, necessitating its inclusion within this hydraulic investigation. The literature within RMA explicitly provide the number of earthquakes that occurred with magnitudes larger than 2.5. Due to the lack of available data with the USGS archives and the critical need to include this location, we supplemented earthquake occurrences from the literature for RMA. This made a total of eleven of the 17 PISAs used in the analyses regarding seismic events.

Table 5.2

Injection Rates and Transmissivities for the 17 USGS PISAs

PISA	Injection Rate Q (m^3/sec)	Transmissivity T (m^2/sec)	Pressure Ratio Q/T (m)
Alabama, Brewton	3.17E-06	~6.34E-04	1.31E+06
Arkansas, Guy-GreenBriar	7.45E-03	~1.08E-05	1.81E+09
Colorado, RMA	7.99E-03	1.08E-05	1.94E+09
Colorado & NM Raton Basin	6.97E-03	~1.34E-04	1.36E+08
Colorado, Greeley	1.81E-02	~2.75E-05	1.73E+09
Colorado, Rangely	3.23E-01	4.30E-03	1.97E+08
Colorado, Paradox Valley	~1.52E-02	~5.05E-02	7.91E+05
New Mexico, Dagger Draw	5.71E-02	~1.26E-02	1.19E+07
Ohio, Youngstown	4.17E-03	~2.94E-12	3.72E+15
Ohio, Ashtabula	1.90E-03	~2.94E-12	1.70E+15
Oklahoma, Central	2.42E-02	~1.61E-02	3.94E+06
Texas, Azle	~1.90E-03	~1.26E-02	3.98E+05
Texas, Cogdell	1.27E-01	~8.06E-04	4.13E+08
Texas, Dallas-FTW	~1.71E-02	~1.26E-02	3.58E+06
Texas, Fashing	~1.87E-02	~1.97E-12	1.99E+16
Texas, Timpson	~1.14E-02	~4.50E-14	6.67E+17

~ Indicates the value was retrieved from state or federal archives, or the value was estimated or calculated based on literature values, injection ranges, or supplementary data from state and federal agencies.

The injection rates listed in Table 5.2 were obtained through PISA research. The peer-reviewed research sources are listed in Table 5.1. Rates were presented in a variety of formats, with average and maximum rates provided most frequently. An average of injection rates were used when a range of rates or annual rates over a length of time were provided. Using these data sets, this research conducted three analyses: (1) A comparison of injection rate versus transmissivity values, (2) A comparison of differential pressure strength (the Q/T or pressure ratio) and earthquake occurrences, and (3) a comparison of the number of earthquake events versus duration of seismic activity.

Results

The initial analysis compared the ratio of transmissivity to injection rates provided in the literature to see if a trend exists using the 16 of 17 PISAs with available injection rates. No correlation among data sets could be made. There were four outliers to the main cluster of data, indicating four locations with transmissivities much smaller than the average. These locations include Fashing, Timpson, Ashtabula, and Youngstown (Figure 5.1). These values for Fashing and Timpson were obtained from USGS reports and the Ashtabula and Youngstown values were from the Ohio Geological Survey (Foote, Massingill, & Wells, 1988; ODNR, 2016). For these four values, it can be assumed these transmissivities were obtained by measurements on core samples, and are not appropriate for further use in this research as representative descriptors of their PISA injection locations. These values are included to illustrate the issue of including matrix permeability values as formation transmissivity estimates in the fractured formations, which generally occurs.

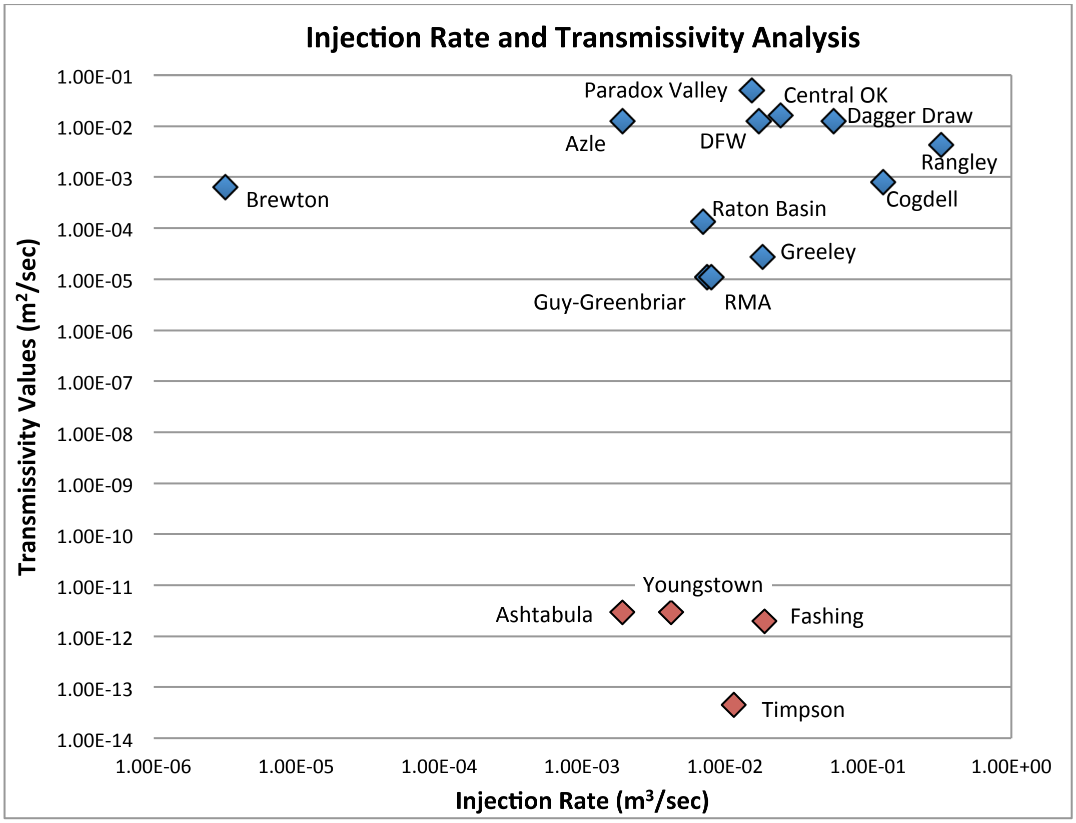

Figure 5.1. The relationship of transmissivity and injection rate. Diamonds represent a PISA location. The red diamonds represent the four locations with atypical transmissivity values.

The analysis of the pressure ratio to the number of earthquakes occurring in the PISA had sufficient data to analyze seven locations. As the pressure ratio increased, the number of felt earthquakes also increased with an r^2 of 0.79 (Figure 5.2). No trend was found by comparing duration of seismic activity and pressure migration (Figure 5.3).

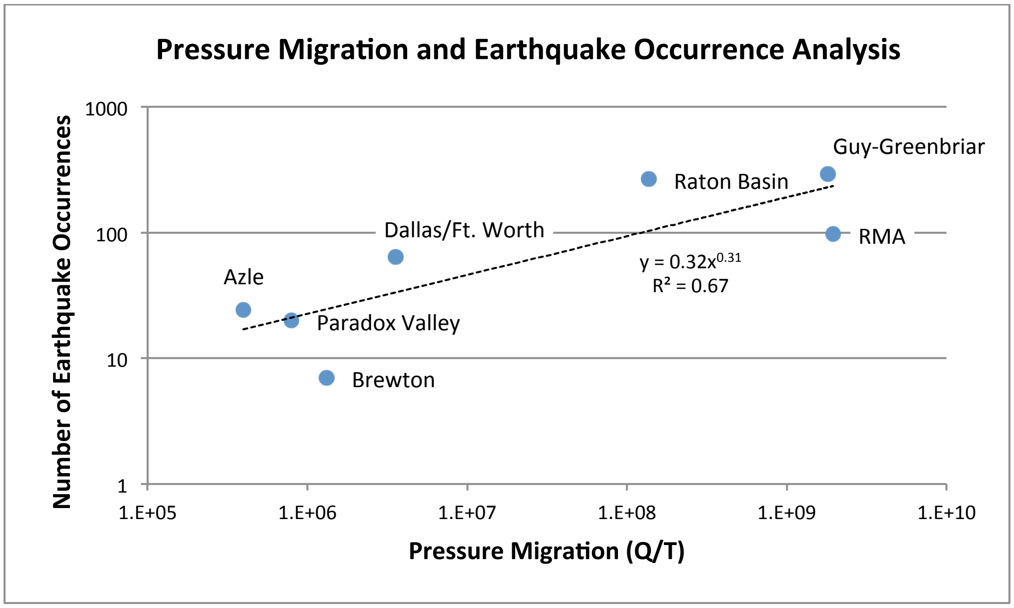

Figure 5.2. Pressure migration compared to earthquake occurrences within seven of the USGS identified PISAs. The r^2 value for the power function and analytical equation of the model are shown.

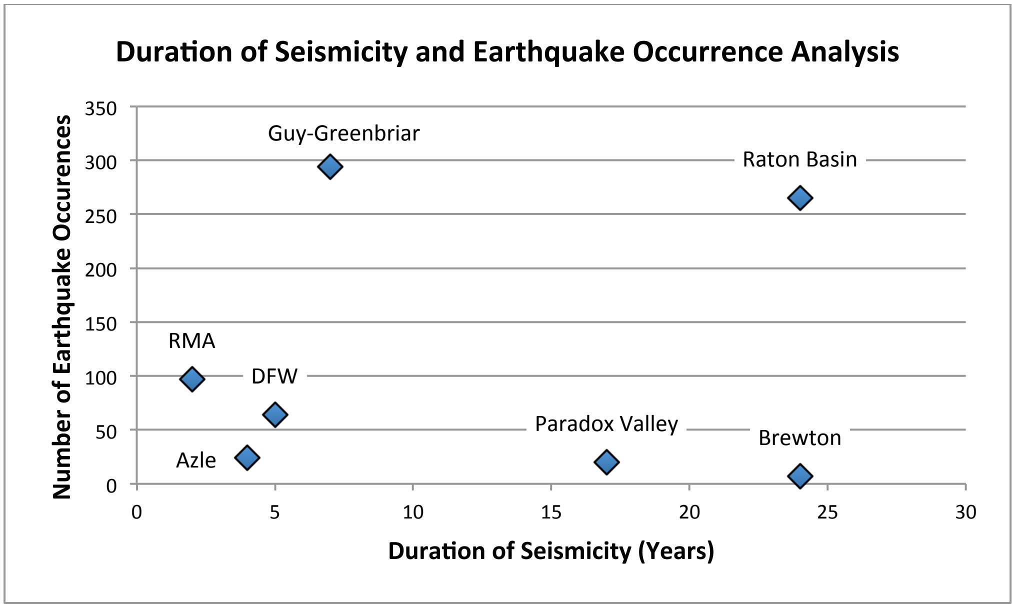

Figure 5.3. Duration of seismicity compared to earthquake occurrences within seven of the USGS identified PISAs. Blue diamonds represent one PISA.

Discussion

This research indicates no significant pattern between transmissivity and injection rate. A trend would indicate a systematic design for injection rates across the various PISAs. This implies the injection rates for these sites are not coordinated with injection interval transmissivities, as supported by the large range of values. In other words, the uncorrelated relationship between injection rate and transmissivity means that on average, injection interval properties are not used to base decisions of rate of injection. In resource production, transmissivity tests are completed to discover the rate of production or yield within the system. Completing site characterizations with transmissivity tests prior to onset of injection would provide reliable estimates for appropriate rates of injection based on waste disposal properties, instead of based purely on production quantities.

Transmissivity can indicate how quickly fluids may move through the formation. The four outlying transmissivities found in the injection rate versus transmissivity analysis are atypically small. With injection formation thicknesses ranging from 98 to 298 m among these four locations, one would expect the transmissivity values to be orders of magnitude larger. Due to the absence of hydrogeologic data within the literature, the hydraulic values used for these locations were compiled from sources with no affiliation with PISAs and are most likely not representative of the formation transmissivity addressed in this research. This scale effect in transmissivity values is common and expected in these formations (Galvao et al., 2016). The transmissivity and permeability values supplementing this research came from a wide variety of texts, journals, federal and state sources, with little to no information provided on how the flow values were captured. These flow values are most likely matrix values not appropriate for formation characterization at depth. This supports the need for hydraulic well tests within PISA locations to obtain site-specific hydraulic data necessary for investigations of fluid induced seismicity. Comparing this study with site-specific transmissivity values from additional sites would help further evaluate the use of hydraulic data for managing injection induced seismicity.

The comparative analysis regarding duration of seismic activity versus number of seismic events showed no significant correlation. Research indicates subsurface fluid pressure may continue to propagate away from the injection well even after injection ceases. This systematic review does not supply significant evidence that length of time has influence over the number of earthquakes a PISA experiences. This analysis supports less emphasis on duration of injection and more influence from hydrogeologic properties of the injection interval and the pressure ratio for the injection well.

The strong correlation among the pressure ratio data to number of earthquakes has significant implications. This analysis indicates an increase in number of felt earthquakes as the pressure differential increases. The power law trend provides an analytical model well designers can use to determine the threat of seismic activity, accounting for two-thirds of the variability within the model. In this research, a pressure ratio of 10^5 m or more is more likely to cause an earthquake than a lower ratio. With site-specific transmissivity data, this analytical model could be used to determine the seismic hazard within a location prone to injection induced seismicity.

Most of the sites included in this study did not have long-term seismic activity. Most PISAs were regulated by a shut down of injection after correlating seismicity to injection. This means the seismic activity and injection timespan is relatively short. Additional considerations should include assessments of preexisting geological conditions. All but one of the PISAs reviewed in this research inject into crystalline basement, carbonates, or formations hydraulically connected to basement through fractures and faulting. The results of this research are consistent among PISAs, or locations already known to be at risk for seismicity due to injection conditions, but may not be representative of all areas with the CEUS. For example, there is ongoing injection within the Bakken formation, North Dakota. A record high of 440 Mbbl of saltwater was injected into the Dakota (Inyan Kara) formation in 2015 through injection disposal wells (Kurz et al., 2016). This formation is sandstone 1.5 km (0.9 miles) deep, not adjacent to the crystalline basement. The state has experienced only 13 felt earthquakes since 1915.

For perspective, Oklahoma injected 1,538,358 Mbbl in 2014 (Murray, 2015) and injects into the vertically permeable Arbuckle formation hydraulically connected to basement. Oklahoma experience 585 earthquakes with magnitudes of 3 or larger (Oklahoma Office of the Secretary of Energy and Environment, 2015). This research recognizes that although there are clear patterns among the locations in this study, there are other locations within the CEUS that may be able to accommodate ongoing injection disposal with higher pressure ratios due to optimal geological conditions. Seismological, structural, and hydrogeologic assessments should be conducted to ascertain which locations are conducive to injection disposal activities.

Conclusion

This research found a correlation between pressure ratio estimations within USGS identified PISAs and earthquake activity, providing an analytical model for estimating earthquake hazard accounting for two-thirds of the variability. There was no correlation with injection rate when compared to transmissivity values, which suggests little to no design consideration for how the injection interval will respond to injection rates prior to onset of injection. The lack of correlation between earthquake occurrence over time when compared to the strong correlation of earthquake occurrence and pressure generation indicates the importance of hydrogeological site characterizations in order to assess seismic hazard due to injection wells.

CHAPTER VI

SUMMARY OF RESULTS

The 17 USGS identified PISAs have all experienced increases in seismic activity. The goal of this systematic review of peer-reviewed research within these PISAs was to discover if hydrogeologic patterns exist across locations. Discovering patterns across various geological settings would allow improved management or reduction of seismic hazard within injection locations.

Recognizing a gap in knowledge and understanding of hydrogeology within PISAs led to investigations in the availability, importance, and trends regarding hydrogeologic data in the scientific literature. Davis and Pennington (1989) established the need for calculating or modeling subsurface pressure migration as it relates to injection disposal wells. Subsurface fluid injection increases pore pressure at critically stressed fault locations, increasing seismic risk. Well hydraulic equations or numerical models of subsurface flow are used to calculate subsurface pressure migration and can be manipulated to account for site-specific conditions. This research, broken into three distinct, but related efforts, investigated aspects of hydrogeology within the 17 USGS identified PISAs.

Conclusions

These investigations revealed a lack of site-specific hydrogeologic data within the 17 USGS identified PISAs. Research efforts recognize these parameters are necessary for estimating subsurface pressure migration. However, these parameters continue to be largely unavailable since capturing these data are not required by state regulatory agencies. Critical parameters include transmissivity, storativity, injection interval thickness, and pressure measurements including baseline pressure. This research provided a systematic method for categorizing scientific certainty of induced seismicity, which can be used by regulatory agencies to establish scientific certainty or lack thereof for potential cases of induced seismicity.

Through analyzing distance of earthquake occurrence from injection disposal wells, this research found an average radius of 47 km (29 miles) where 90% of earthquakes occurred within the current PISAs. Nearest seismic events occur between 2.0 km (1 mile) away from injection wells. Investigation within a 10 km (6.2 miles) radius surrounding injection disposal wells will account for 50% of seismic activity. Estimating hydrogeologic parameters based on tables or common values may not provide reliable results for pressure migration modeling. It is critical to obtain site-specific hydrogeologic values with hydraulic tests throughout the injection interval to create reliable pressure migration models. An analysis of pressure ratios (Q/T) compared to the number of seismic events within PISAs provided an analytical method for predicting seismic activity accounting for two thirds of the variability with a power law correlation.

Implications

The implications of this research lie with regulators and petroleum production companies, which rely on scientific evidence for best practices implementation. Firstly, this research identifies large gaps in hydrogeologic knowledge critical to managing injection disposal wells. A reliable understanding of hydrogeologic conditions allows for effective management of seismic hazard zones and provides a potentially proactive approach to preventing seismic hazard. Secondly, the radius of hazard surrounding injection disposal wells provides a more uniform view of the phenomenon to aid in improving regulatory standards. Regulators and well operators can continuously monitor hydrogeologic activity and fault locations within this radius to ensure a reduction in seismic hazard. Thirdly, hydrogeologic conditions are not easily estimated. The varied nature of subsurface properties provides site-specific conditions difficult to accurately model. Actual hydrogeologic measurements within the targeted system allows for more accurate modeling of flow patterns and seismic risk.

Recommendations and Future Research

As mentioned previously, investigating induced seismicity requires a multidisciplinary approach, where structural geology, seismology, and hydrogeology are integrated to evaluate site-specific conditions near injection disposal well locations. This research focused on hydrogeology, and the importance of understanding fluid flow in PISAs. There are other concerns, which hinder induced seismicity research. Walsh and Zoback (2015) emphasized the importance of locating and understanding geological conditions, and argued these factors may even be more important than flow descriptions of the area. Earthquake magnitude is dependent on size, length, and orientation of the fault (Wells & Coppersmith, 1994): justifying the need for mapping fault structures in the subsurface, particularly crystalline basement. This research validates the critical need for site-specific hydrogeologic characteristics. Successfully determining the seismic risk of an area lies with the most complete understanding possible for all of the conditions, but this research indicates hydrogeologic conditions are generally neglected for site characterization of injection areas.

Efforts should be made to map crystalline basement and injection intervals to identify critically stressed faults. Injection should be limited to locations with a sedimentary basal seal to limit flow into the basement (Zhang et al., 2013). Federal and state agencies should require hydraulic tests as part of injection monitoring and prior to injection well establishment. Hydraulic tests should be conducted at well locations, and seismic or hydraulic monitoring in a zone with a radius of at least 48 km (30 miles) to monitor flow conditions as injection occurs. Preferably, characterization would be conducted prior to injection disposal well establishment to identify potential seismic issues with the injection site. For currently operating injection disposal wells, the traffic light system should be implemented to ensure well operators are maintaining appropriate injection rates and volumes for their region.

Future research regarding induced seismicity includes obtaining site-specific hydrogeologic values within current PISAs, and conducting a systematic review with more complete datasets. Researchers and state agencies should place efforts in locating critically stressed fault structures capable of producing felt earthquakes with magnitude 2.5 or greater. With fault data, researchers may then be able to determine whether an area is conducive to fluid injection based on hydrogeologic and structural data. Injection rates, volumes, and pressure measurements may then be regulated to maintain as low of seismic hazard as possible.

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APPENDICES

Appendix A

Injection Interval Data Compilation

	Location	**Well Name**	**Injected formation**	**Injection Depth (m)**	**Thickness (m)**	**Reference**
1	Alabama, Brewton	average	Tuscaloosa Group sandstone/shale	2100	800	Gomberg et al. (1999)
2	Alabama, Brewton	77242	Tuscaloosa Group sandstone/shale	2100	800	Mallory (1993)
3	Alabama, Brewton	74112	Tuscaloosa Group sandstone/shale	2100	800	Clarke (1965)
4	Arkansas, Guy-GreenBriar	1	Springfield/Ozark Aquifer	1821-1969	965	Horton (2012)
5	Arkansas, Guy-GreenBriar	2	Springfield Aquifer (Boone Formation)	1982-2009	965	Horton (2012)
6	Arkansas, Guy-GreenBriar	3	Springfield/Ozark Aquifer	2365-3231	965	Horton (2012)
7	Arkansas, Guy-GreenBriar	4	Springfield/Ozark Aquifer	1713-1926	965	Horton (2012)
8	Arkansas, Guy-GreenBriar	5	Ozark Aquifer, connected to Green-Briar Fault in Precambrian Basement (Arbuckle/Knox Group)	2379-3344	965	Horton (2012)
9	Arkansas, Guy-GreenBriar	6	Western Interior Plains Confining System	678-706	965	Horton (2012)
10	Arkansas, Guy-GreenBriar	7	Ozark Aquifer, connected to Green-Briar Fault in Precambrian Basement	1383-1859	965	Horton (2012)
11	Arkansas, Guy-GreenBriar	8	Western Interior Plains Confining System	647-864	965	Horton (2012)
12	Colorado, RMA		Precambrian Basement	3671		Healy et al. (1968) & Evans (1966)
13	Colorado, Raton Basin		Dakota formation (buff conglomeritic sandstone)	1250-2100	850	Rubinstein et al. (2014)
14	New Mexico, Raton Basin		Dakota formation (buff conglomeritic sandstone)	1250-2100	850	Rubinstein et al. (2014)
15	Colorado, Greeley					Yeck et al. (2014)
16	Colorado, Rangely		Weber sandstone	2286	408	Raleigh et al. (1976)
17	Colorado, Paradox Valley		Mississippian Leadville Limestone & basement	4300 - 4800	127	Horton (2012) & Ake et al. (2005)
18	Colorado, Paradox Valley		Mississippian Leadville Limestone & basement	4300 - 4800	127	Horton (2012) & Ake et al. (2005)
19	New Mexico, Dagger Draw		vuggy limestone	3400		Sanford et al. (2006), Tinker et al. (2004) & Herzog (2014)
20	Ohio, Youngstown	Northstar 1	Knox Dolomite, Mt. Simon Sandstone, & basement	2504-2802	~298	Kim (2013)
21	Ohio, Ashtabula		Mt. Simon Sandstone			Seeber et al. (2004)
22	Central Oklahoma	average				Keranen et al., (2013 & 2014)
23	Central Oklahoma	1	Simpson Group, Limestone/Shale	1120	150	Keranen et al. (2013)
24	Central Oklahoma	2	Arbuckle Group, Limestone	1390	550-950	Keranen et al. (2013)
25	Central Oklahoma	3	Arbuckle Group, Limestone	1800	550-950	Keranen et al. (2013)
26	Central Oklahoma	1	Arbuckle Group, Carbonate	2200 - 3500	1300	Keranen et al. (2014)

	Location	Well Name	Injected formation	Injection Depth (m)	Thickness (m)	Reference
27	Central Oklahoma	2	Arbuckle Group, Carbonate			Keranen et al. (2014)
28	Northern OK Southern KS		Mississippi Limestone			Rubinstein et al. (2014) & Walsh & Zoback (2015)
29	Texas, Azle	average	Ellenberger Dolomite	2000-3000	~1000	Hornbach et al. (2015)
30	Texas, Azle	Injector well 1	Ellenberger Dolomite	2000-3000	~1000	Hornbach et al. (2015)
31	Texas, Azle	Injector well 2	Ellenberger Dolomite	2000-3000	~1000	Hornbach et al. (2015)
32	Texas, Fashing	average				Pennington et al. (1986), Davis et al. (1995), Frohlich & Brunt (2013)
33	Texas, Fashing	gas extraction	Edwards Limestone	3400	~100	Pennington et al. (1986)
34	Texas, Fashing	hydrocarbon extraction	Edwards Limestone	3200	~100	Davis et al. (1995)
35	Texas, Fashing	API14201007611				Frohlich & Brunt (2013)
36	Texas, Cogdell	average	Canyon Reef Limestone	2100	45	Gan & Frohlich (2013), Davis & Pennington (1989)
37	Texas, Cogdell	water injection	Canyon Reef Limestone	2100	45	Davis & Pennington (1989)
38	Texas, Cogdell	gas injection	Canyon Reef Limestone	2100	45	Gan & Frohlich (2013)
39	Texas, Dallas-FTW	average	Ellenberger Dolomite	3300 - 4200	760	Frohlich et al. (2010, 2011, & 2012)
40	Texas, Dallas-FTW	North	Ellenberger Dolomite	3300 - 4200	760	Frohlich et al. (2010, 2011, & 2012)
41	Texas, Dallas-FTW	South	Ellenberger Dolomite	3301 - 4200	760	Frohlich et al. (2010, 2011, & 2012)
42	Texas, Timpson	average	Rodessa – Trinity	1800 - 1900	98	Frohlich et al. (2014)
43	Texas, Timpson	North	Rodessa – Trinity	1800 - 1900	98	Frohlich et al. (2014)
44	Texas, Timpson	South	Rodessa – Trinity	1801 - 1900	98	Frohlich et al. (2014)
45	Texas, Timpson	north-2	Rodessa – Trinity	1802 - 1900	98	Frohlich et al. (2014)
46	Texas, Timpson	south -2	Rodessa – Trinity	1803 - 1900	98	Frohlich et al. (2014)

Appendix B

Injection Well Data Compilation

	Location	Well Type/Injectant	Total Volume (m^3)	Initial Injection Date	Final Injection Date
1	Alabama, Brewton	brine			
2	Alabama, Brewton			1980	1997 (as of publication)
3	Alabama, Brewton			1975	1997 (as of publication)
4	Arkansas, Guy-GreenBriar			7/7/10	3/3/11
5	Arkansas, Guy-GreenBriar			4/15/09	6/20/11
6	Arkansas, Guy-GreenBriar			6/15/09	7/27/11
7	Arkansas, Guy-GreenBriar			1/15/10	10/15/10
8	Arkansas, Guy-GreenBriar			8/16/10	3/3/11
9	Arkansas, Guy-GreenBriar			4/5/10	
10	Arkansas, Guy-GreenBriar			1/15/10	
11	Arkansas, Guy-GreenBriar			1/15/11	
12	Colorado, RMA	chemical waste	600,000	3/8/62	
13	Colorado, Raton Basin	IDW	~17,488,603	1994	
14	New Mexico, Raton Basin	IDW	6,072,125	1999	2005 (as of publication)
15	Colorado, Greeley			Aug 2013	
16	Colorado, Rangely			1962	1973
17	Colorado, Paradox Valley		4,000,000	7/11/91	
18	Colorado, Paradox Valley	Class V SWD	7,600,000		
19	New Mexico, Dagger Draw	IDW	14,500,000	1994	2004 (as of publication)
20	Ohio, Youngstown	IDW	78,798	12/29/10	12/30/11
21	Ohio, Ashtabula	class 1 well	340,000	1986	1994
22	Central Oklahoma				
23	Central Oklahoma	IDW	~130,000	1993	2011 (as of publication)
24	Central Oklahoma	IDW			
25	Central Oklahoma	IDW			
26	Central Oklahoma	IDW			
27	Central Oklahoma	IDW			
28	Northern OK Southern KS				
29	Texas, Azle				
30	Texas, Azle	IDW		Jun-09	
31	Texas, Azle	IDW		Oct-10	
32	Texas, Fashing				
33	Texas, Fashing	fluid and gas withdrawal		1958 (production)	
34	Texas, Fashing				
35	Texas, Fashing	IDW		2004	
36	Texas, Cogdell				
37	Texas, Cogdell	SWD	3,700,000	Apr-56	
38	Texas, Cogdell	methane and CO2			
39	Texas, Dallas-FTW				
40	Texas, Dallas-FTW	SWD			
41	Texas, Dallas-FTW	SWD	38,687 - 48,357	11/12/08	Jun-09
42	Texas, Timpson				
43	Texas, Timpson	IDW	1,050,000	2006	2007
44	Texas, Timpson	IDW	2,900,000	Sep-06	2007
45	Texas, Timpson	IDW		Mar-09	
46	Texas, Timpson	IDW		Apr-09	Jan-10

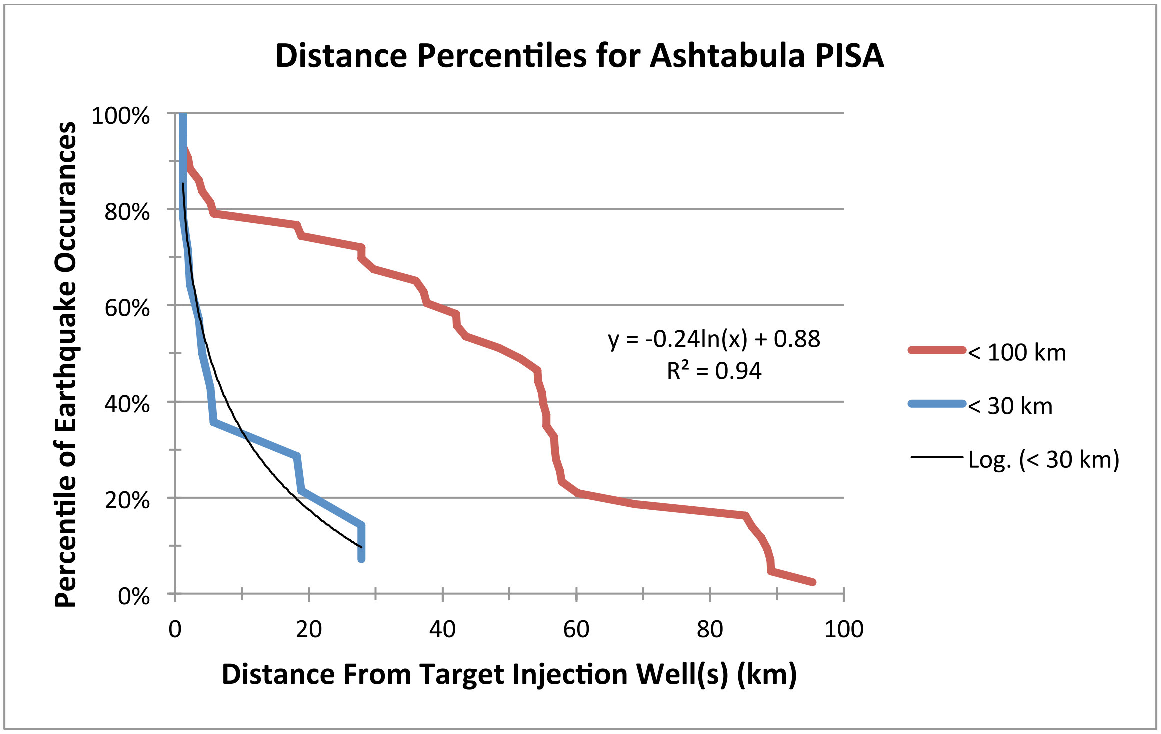
Appendix C

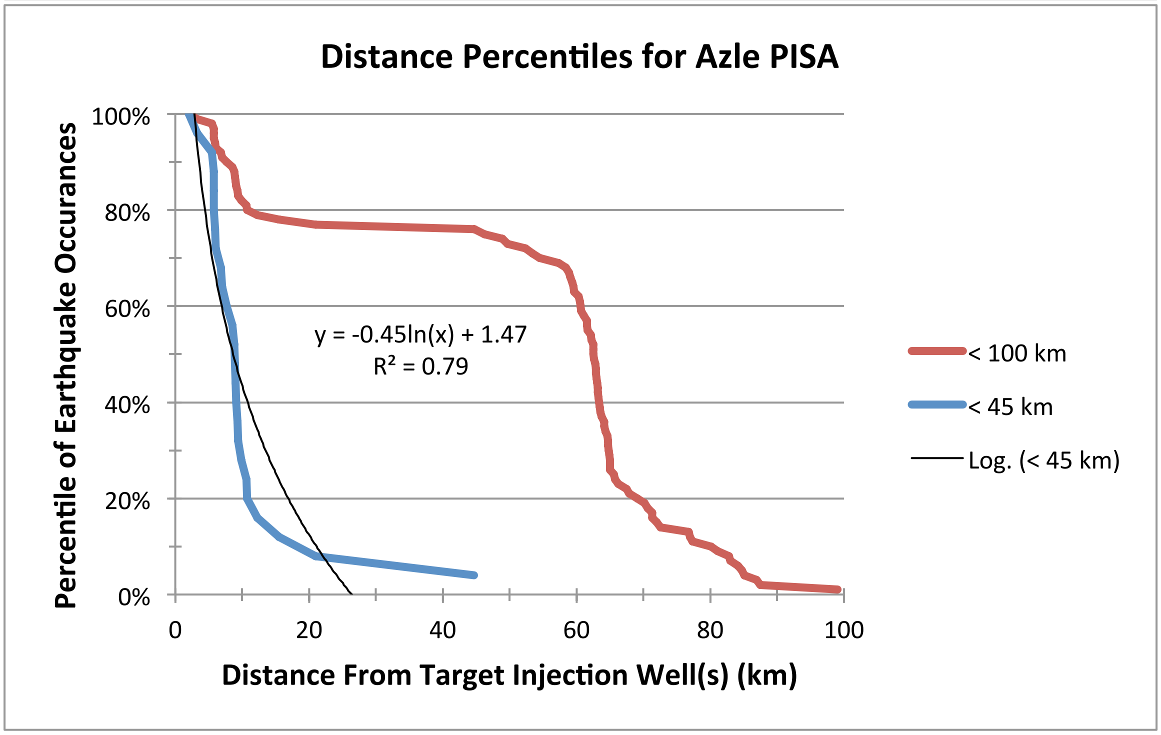
Hydrogeology Data Compilation

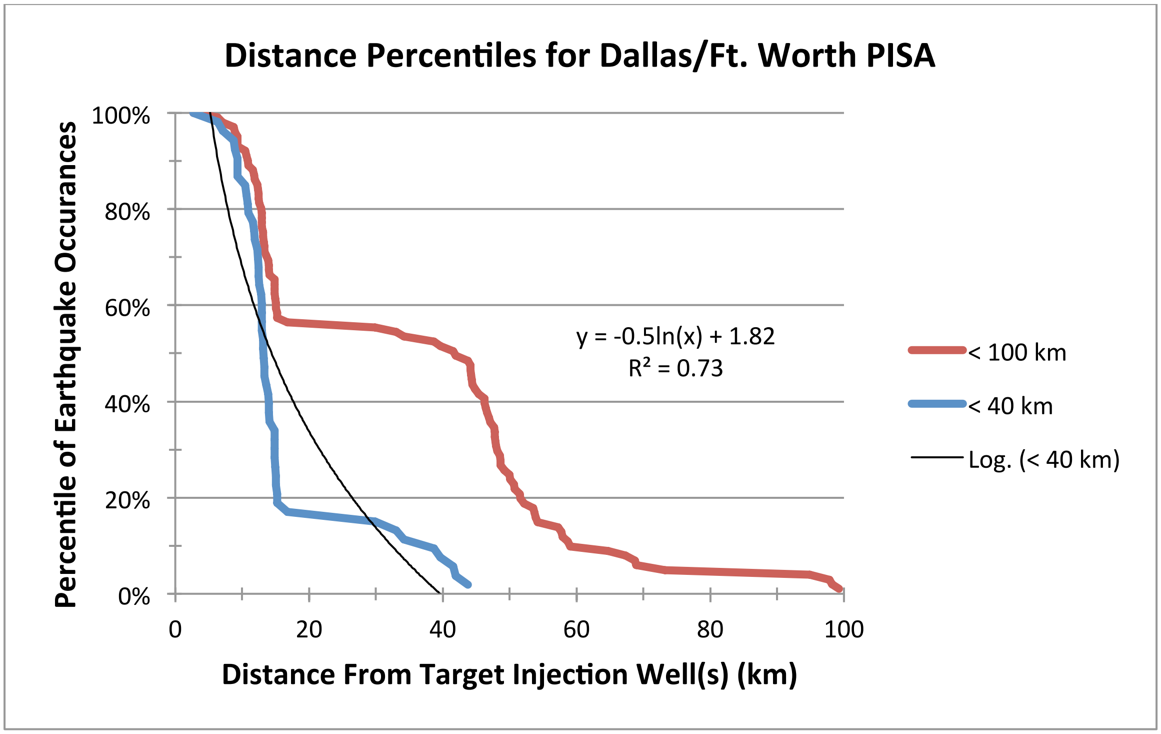
	Location	Transmissivity (m^2/day)	Effective Porosity/ Porosity	Permeability/Hydraulic Conductivity	Storage
1	Alabama, Brewton		"vary significantly"	"vary significantly"	
2	Alabama, Brewton				
3	Alabama, Brewton				
4	Arkansas, Guy-GreenBriar		4-6%		
5	Arkansas, Guy-GreenBriar				
6	Arkansas, Guy-GreenBriar		4-6%		
7	Arkansas, Guy-GreenBriar		4-6%		
8	Arkansas, Guy-GreenBriar	~1.08×10^{-5}	4-6%		~10^{-5}
9	Arkansas, Guy-GreenBriar				
10	Arkansas, Guy-GreenBriar	~1.08×10^{-5}	4-6%		~10^{-5}
11	Arkansas, Guy-GreenBriar				
12	Colorado, RMA	1.08×10^{-5}			10^{-5}
13	Colorado, Raton Basin				
14	New Mexico, Raton Basin				
15	Colorado, Greeley				
16	Colorado, Rangely	1.48×10^{-11} to 2.96×10^{-11}	12%	0.1 mD	
17	Colorado, Paradox Valley				
18	Colorado, Paradox Valley		<10%	<10 mD	
19	New Mexico, Dagger Draw				
20	Ohio, Youngstown		9.4-10.3%		
21	Ohio, Ashtabula				
22	Central Oklahoma				
23	Central Oklahoma				
24	Central Oklahoma				
25	Central Oklahoma				
26	Central Oklahoma				
27	Central Oklahoma				
28	Northern OK Southern KS				
29	Texas, Azle			10^{-14} to 10^{-15} m^2	
30	Texas, Azle			10^{-19} to 10^{-20} m^2 (underlying basement)	~10^{-6} to 13×10^{-6}
31	Texas, Azle				
32	Texas, Fashing				
33	Texas, Fashing		15%	12.6 mD	
34	Texas, Fashing				
35	Texas, Fashing				
36	Texas, Cogdell				
37	Texas, Cogdell		10%	9×10^{-15} m^2	1.5×10^{-4}
38	Texas, Cogdell				
39	Texas, Dallas-FTW			10^{-14} to 10^{-15} m^2	
40	Texas, Dallas-FTW			10^{-19} to 10^{-20} m^2 (underlying basement)	
41	Texas, Dallas-FTW				
42	Texas, Timpson				
43	Texas, Timpson				
44	Texas, Timpson				
45	Texas, Timpson				
46	Texas, Timpson				

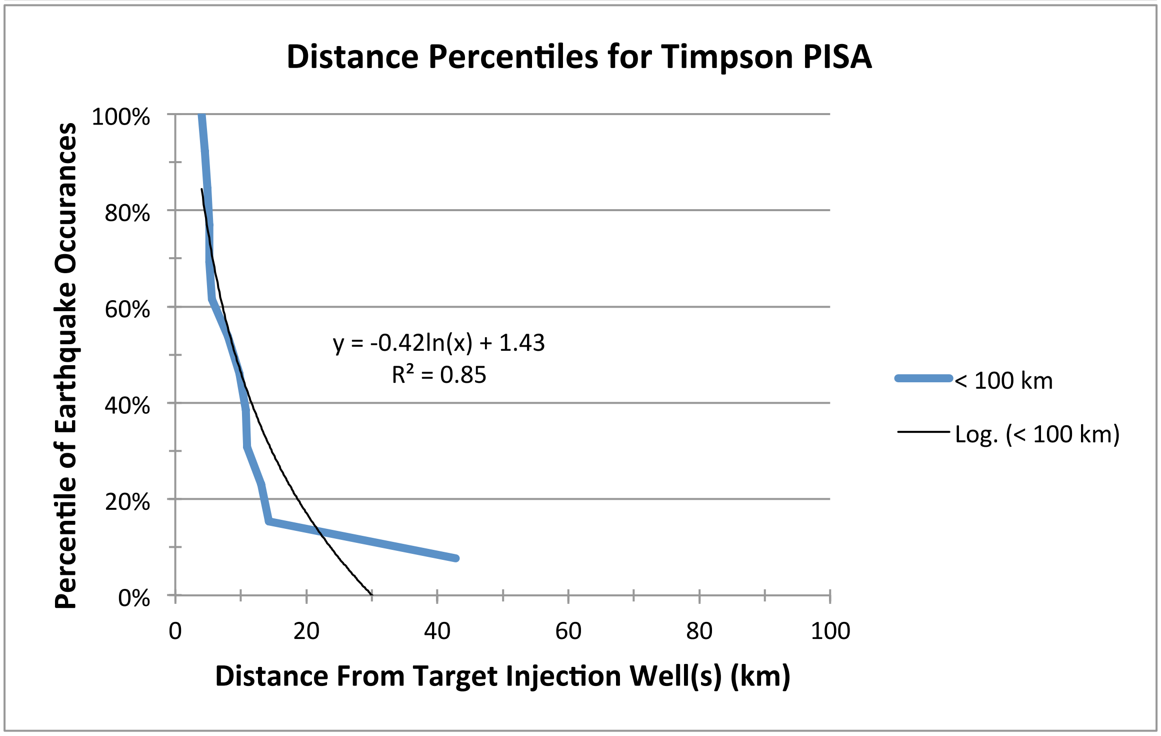
Appendix D

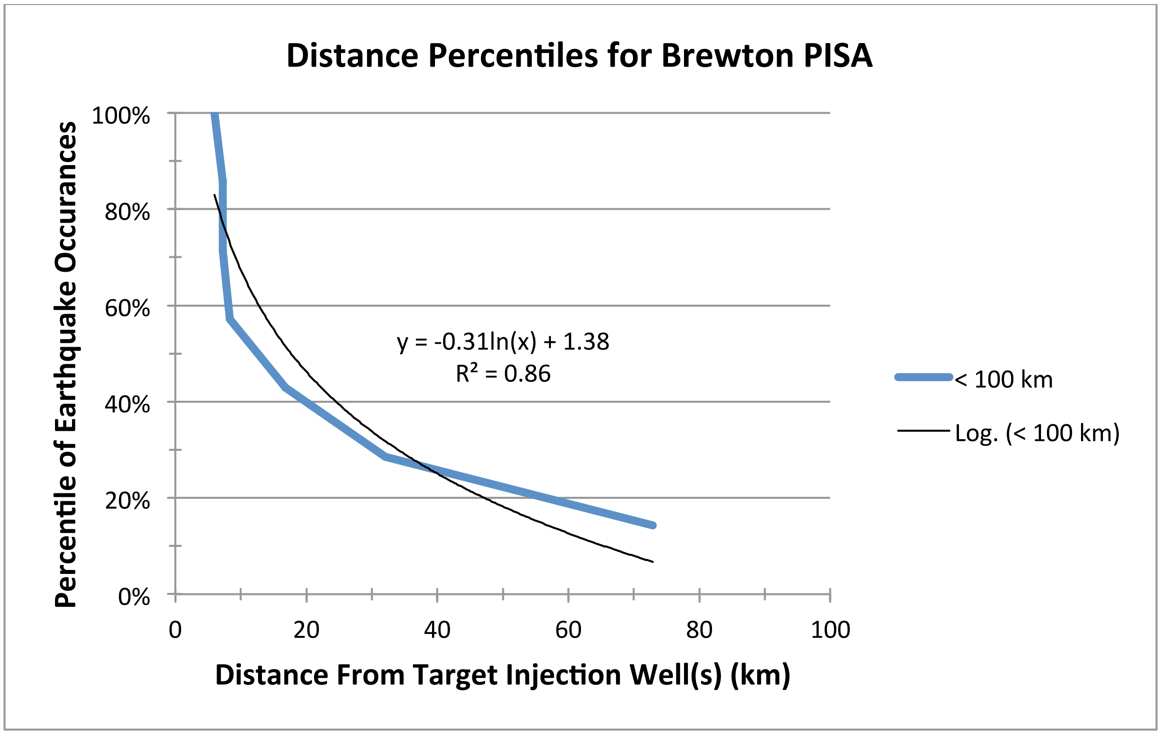
Distance Percentiles of Potentially Induced Seismic Areas and Composite

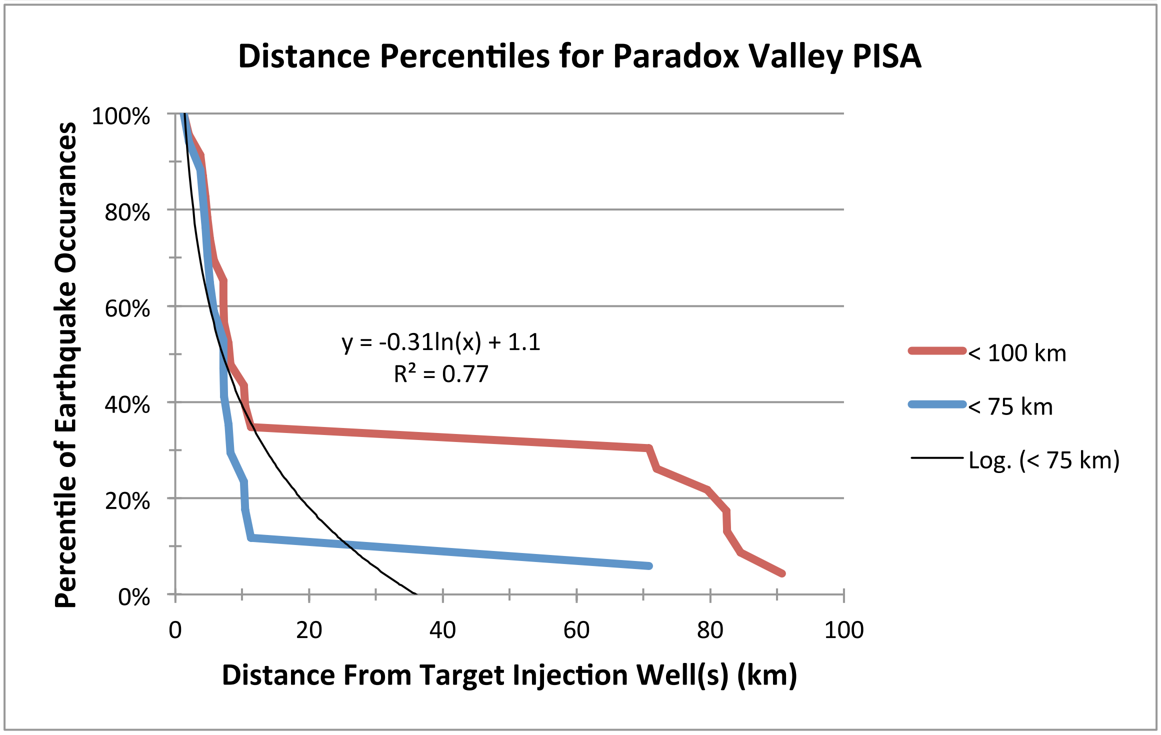


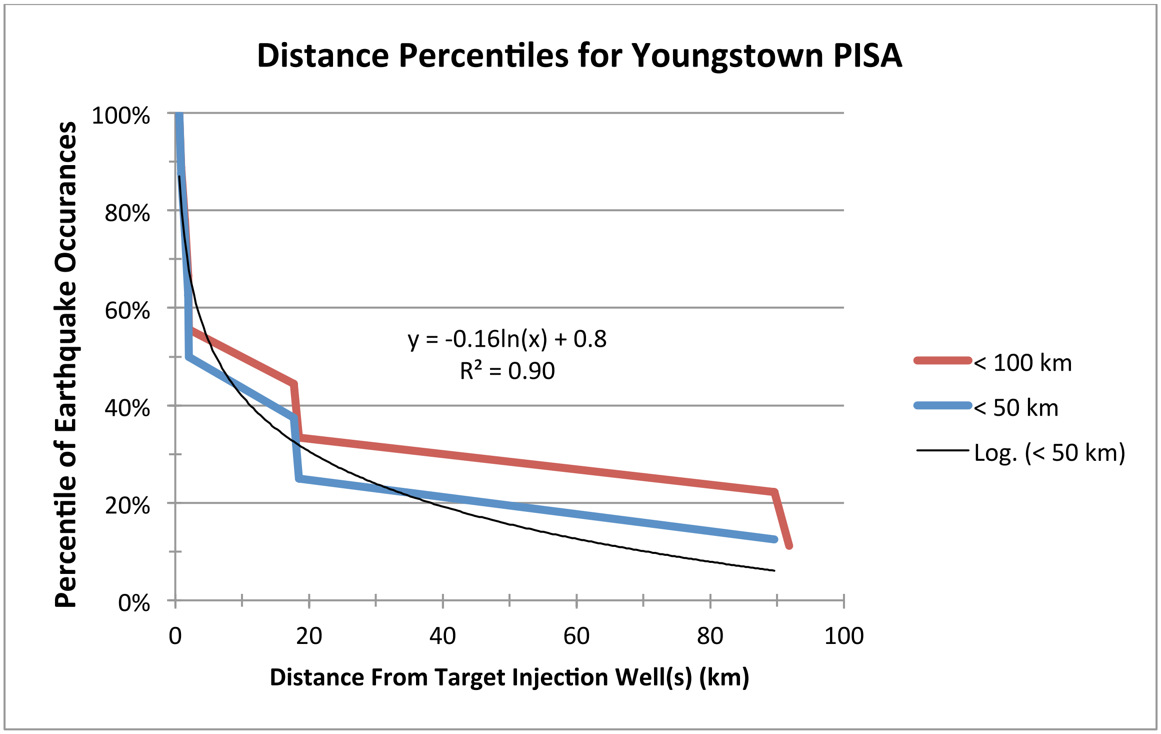


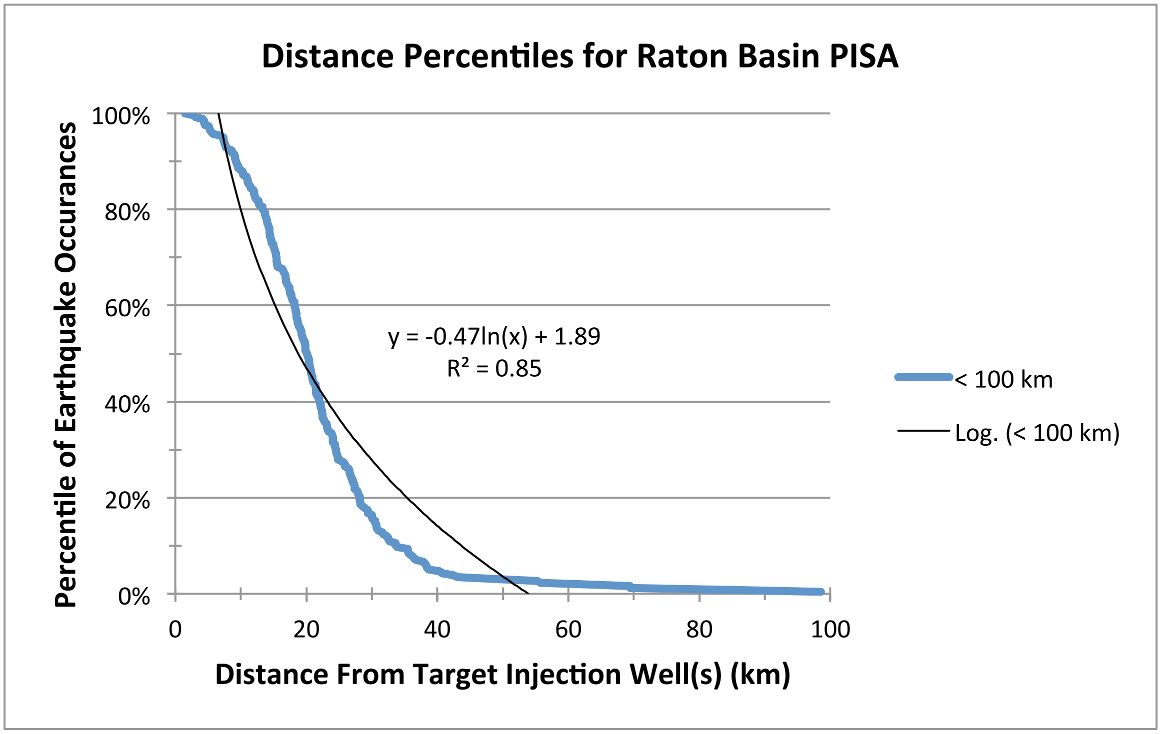

Distance Percentiles for Dallas/Ft. Worth PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.5ln(x) + 1.82
R² = 0.73
< 100 km
< 40 km
Log. (< 40 km)

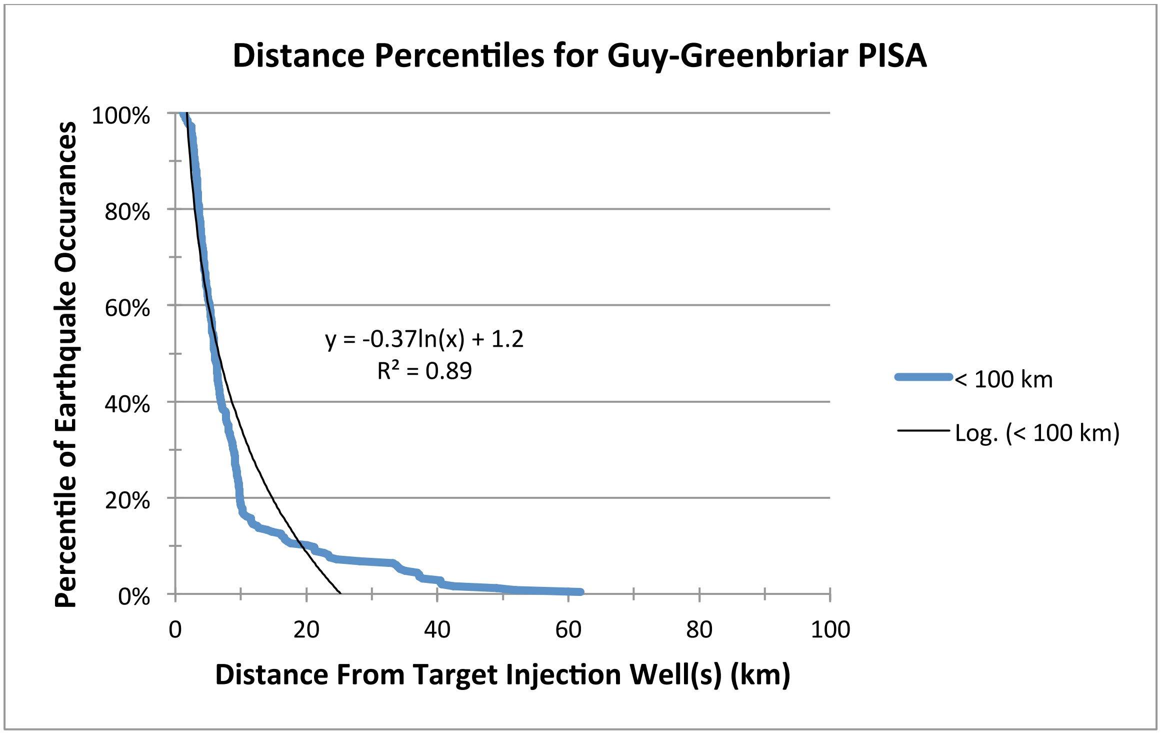

Distance Percentiles for Timpson PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.42ln(x) + 1.43
R² = 0.85
< 100 km
Log. (< 100 km)

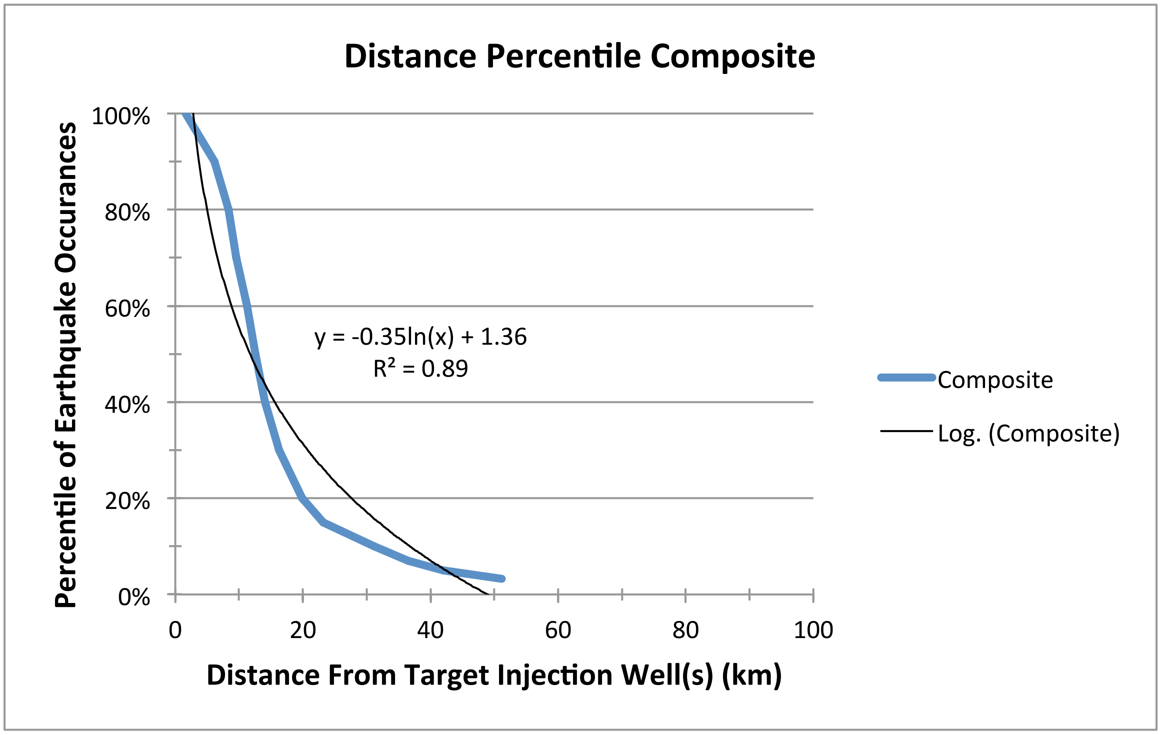

Distance Percentiles for Brewton PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.31ln(x) + 1.38
R² = 0.86
< 100 km
Log. (< 100 km)


Distance Percentiles for Paradox Valley PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.31ln(x) + 1.1
R² = 0.77
< 100 km
< 75 km
Log. (< 75 km)


Distance Percentiles for Youngstown PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.16ln(x) + 0.8
R² = 0.90
< 100 km
< 50 km
Log. (< 50 km)


Distance Percentiles for Raton Basin PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.47ln(x) + 1.89
R² = 0.85
< 100 km
Log. (< 100 km)


Distance Percentiles for Guy-Greenbriar PISA
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.37ln(x) + 1.2
R² = 0.89
< 100 km
Log. (< 100 km)


Distance Percentile Composite
Percentile of Earthquake Occurances
100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Distance From Target Injection Well(s) (km)
y = -0.35ln(x) + 1.36
R² = 0.89
Composite
Log. (Composite)

Appendix E

Definition of Terms

Aquifer – “Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs” (Fetter, 1994, p. 552)

Advective migration – The generally laminar flow of fluids through porous rock or sediment

Aseismic – “Said of an area that is not subject to earthquakes” (Bates & Jackson, 1987, p. 40)

Basement – “Igneous or metamorphic rocks, often Precambrian, that unconformably underlie unmetamorphosed sedimentary strata” (Smith, 1981, p. 468)

Baseline pressure – “A starting point of pressure for comparisons” (Hyne, 2014, p. 35)

Borehole – “A hole advanced into the ground by means of a drilling rig” (Fetter, 1994, p 553)

Bottomhole – “The lowest point in a well” (Hyne, 2014, p. 49)

Brine – “A term used for pore fluids in a deep sedimentary basin containing 35% or more dissolved salts” (Bates & Jackson,1987, p. 86)

Casing – (well casing) “A solid piece of pipe, typically steel or PVC plastic, used to keep a well open in either unconsolidated materials or unstable rock” (Fetter, 1994, p. 560)

Crosslinkers – A chemical bond that links one polymer chain to another

Declustered (nondeclustered) – A statistical distribution of size and space clustered by time. Declustering is used to get the best possible estimates for the rate of events (van Stiphout, Zhuang, & Marsan, 2012).

Diffusive migration – Describes a type of ground water flow where the fluids move through conduits or pathways of least resistance (Sharp, 2003)

Diffusivity – "The ratio of [hydraulic] conductivity to storage capacity" (Sharp, 2003, p. 16)

Dissolution – "The process in which a solid or liquid becomes dissolved in water or ground water" (Sharp, 2003, p. 17)

Drawdown – "A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells" (Fetter, 1994, p. 554)

Effective porosity – "The volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment" (Fetter, 1994, p. 558)

Epicenter – "The point on the earth's surface vertically above the point in the earth's cures where seismic rupture begins" (Epicenter, 2016)

Fault – "A fracture along which rocks have been displaced in a horizontal, vertical, or oblique sense" (Smith, 1981, p. 471)

Formation – "A body of rock strata that consists of a certain lithology or combination of lithologies; a lithological unit" (Sharp, 2003, p. 22)

Grab sampling – "A sample taken at a particular place and time" (Sharp, 2003, p. 24)

Hydraulic conductivity – “A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and the kinematic viscosity of the water must be considered in determining hydraulic conductivity” (Fetter, 1994, p. 555)

Hydraulic fracturing (fracking) – A petroleum product retrieval process where fractures are created by the human-induced fluid pressure (Sharp, 2003, p. 27)

Hydrocarbon – “Organic compounds consisting primarily of hydrogen and carbon, including those which occur in petroleum, natural gas, and coal” (Smith, 1981, p. 472)

Hydrogeology – “The study of the interrelationships of geologic materials and processes with water, especially ground water” (Fetter, 1994, p. 556)

Hypocenter – “The point within the earth where an earthquake rupture starts. Also commonly termed the focus” (Hypocenter, 2016)

Homogeneous – “Pertaining to a substance having identical characteristics everywhere. A synonym is uniform” (Fetter, 1994, p. 555)

Induced seismicity – The process of triggering earthquakes through industrial or man-made processes (Simpson, 1986)

Injection interval – A formation or aquifer “used for the injection of fluids for any purpose, including artificial recharge and waste disposal” (Sharp, 2003, p. 29)

Intrinsic permeability – “Pertaining to the relative ease with which a porous medium can transmit a liquid under hydraulic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field” (Fetter, 1994, p. 556)

Isotropic – “The condition in which hydraulic properties of the aquifer are equal in all directions” (Fetter, 1994, p.556)

Karst – “Rocks that have undergone significant dissolution by ground water flow and are characterized by closed depressions of various size and arrangement, disrupted surface drainage, and caves and underground drainage systems” (Sharp, 2003, p. 30)

Lithology – “The general physical (usually visible) characteristics of rocks” (Smith, 1981, p. 473)

Magnitude – “A measure of the strength of an earthquake, or the strain energy released by it, as determined by seismographic observations” (Bates & Jackson, 1987, p. 205)

Media – The substance, generally rock or sediment, through which ground water flows

Paleoliquifaction – “The transformation of loosely packed sediment into a fluid mass preliminary to movement of turbidity current by subaqueous slumping or sliding” (Paleo means ancient, thus paleoliquifaction is ancient evidence of liquefaction; Bates & Jackson, 1987, p. 382)

Play – “Petroleum traps of a particular genetic type, e.g., reef play and growth fault play” (Selley & Sonnenberg, 2014, p. 460)

Permeability – “The capacity of a rock to allow water or other liquids to pass through it, being pervious” (Smith, 1981, p. 474)

Porosity – “The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment” (a pore is the void space, porous means having porosity; Fetter, 1994, p. 558)

Proppant – A solid material, generally sand, used to hold open man-made fractures during the hydraulic fracturing process (Huitt, et al., 2004)

Propagation – Transmission of pressure or fluids in the subsurface

Reservoir – “A highly porous and permeable mass of rock that is able to hold or transmit fluids” (Smith, 1981, p. 476)

Storativity – “The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness” (Fetter, 1994, p. 559)

Specific storage – “The volume of ground water an aquifer absorbs or expels from a unit volume when the pressure head decreases or increases by a unit amount” (Fetter, 1994, p. 559)

Strata – Layers of sedimentary rock

Theis equation – “An equation for the flow of ground water in a fully confined aquifer” (Fetter, 1994, p. 560)

Transmissivity – “The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media” (Fetter, 1994, p. 560)

Wellhead – The structure over a well where the borehole meets the surface.

Appendix F

List of Acronyms

ANSS ComCat – Advanced National Seismic System Comprehensive Catalog

COGCC – Colorado Oil and Gas Corporation Commission

CEUS – Central and Eastern United States

EPA – U.S. Environmental Protection Agency

NMSZ – New Madrid Seismic Zone

NRC – National Research Council

NSHM – National Seismic Hazard Model

PISA – Potentially Induced Seismic Area

RCRA – Resource Conservation and Recovery Act

RMA – Rocky Mountain Arsenal

SDWA – Safe Drinking Water Act

UIC – Underground Injection Control

USGS – United States Geological Survey

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