UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

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OFFICE OF WATER

MEMORANDUM

SUBJECT: Distribution of Final Work Product from the National Underground Injection Control (UIC) Technical Workgroup - *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*

FROM: Ronald Bergman, Acting Director
Drinking Water Protection Division (4606M)
Office of Ground Water and Drinking Water

TO: UIC Program Managers
EPA Regions I-X

The Office of Ground Water and Drinking Water is pleased to provide the final product of the UIC National Technical Workgroup (NTW) entitled, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches.* The report will be a valuable tool for UIC program managers addressing induced seismicity.

Within the past few years, many small to moderate magnitude earthquakes have been recorded in areas with Class II waste disposal injection wells (II-D) related to unconventional oil and gas production. To address the growing public concern that induced seismicity could endanger drinking water sources, EPA's Drinking Water Protection Division requested that the NTW develop a report with practical management tools to help federal and state UIC regulators address potential injection-induced seismicity.

The NTW was formed in 1995 to discuss technical issues related to the UIC Program and is comprised of staff from each EPA Regional Office, OGWDW, and select states authorized to implement the UIC program. The NTW provides a forum whereby technical issues relating specifically to the UIC Program can be discussed, reviewed and resolved by UIC program experts. The NTW provides an avenue for open dialogue, communication, and coordination between EPA and State representatives concerning technical matters related to underground injection as defined in the Safe Drinking Water Act (42 USC 6A, Part C). States with extensive programmatic experience in addressing induced seismicity participated in the development of this report, including Ohio, Colorado, Oklahoma, Texas, West Virginia, and Arkansas. A number of these states have developed state regulations or guidelines addressing induced seismicity and each of the states contributed valuable experience and expertise to this effort.

The NTW was tasked with summarizing the available information on induced seismicity and providing specific suggestions for managing induced seismicity within the context of the Class II UIC program.

The NTW developed the attached report using the existing Class II regulatory framework to recommend strategies for managing and minimizing the potential for significant injection-induced seismic events. The approaches in the report are non-regulatory in nature, and are within the Class II Director's discretion to apply. The report recommends practical steps to reduce the potential for induced seismicity in the areas of site assessment, well operation, monitoring, and management. It can help UIC managers evaluate the potential for induced seismicity in a planned injection operation, and describes permit conditions that can be added to manage this potential, so that oil and gas wastewater disposal operations can continue with adequate environmental safeguards.

The NTW report was informed by an extensive review of the technical literature on induced seismicity and evaluation of case study examples in Arkansas, Ohio, Texas, and West Virginia. The NTW considered data availability and variations in geology and reservoir characteristics. The draft report benefited from expert peer consultation and was submitted for independent scientific peer review prior to being finalized.

We are providing a copy of this report to you so you may distribute it to EPA and state UIC program personnel in your region and encourage UIC regulators to utilize the available tools and lessons learned to reduce the potential for injection-induced seismic events. The report is available on EPA's UIC website: http://www.epa.gov/r5water/uic/techdocs.htm. If you have any questions, please contact Bill Bates at (202) 564-6165.

Attachment

cc: (w/attachment)
Michel Paque, Executive Director - GWPC
Michael Smith, Executive Director - IOGCC

MINIMIZING AND MANAGING POTENTIAL IMPACTS OF INJECTION-INDUCED SEISMICITY FROM CLASS II DISPOSAL WELLS: PRACTICAL APPROACHES

Underground Injection Control National Technical Workgroup
U.S. Environmental Protection Agency
Washington, DC

Draft: December 24, 2013
Revised: November 12, 2014

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EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) program regulates injection of fluids related to oil and gas production as Class II injection wells for the protection of underground sources of drinking water (USDWs). Because seismic events from injection have the potential to cause endangerment of underground sources of drinking water, the UIC program director should be aware of that potential and be prepared with response options should seismic events become a concern. Unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have expanded the geographic area for oil and gas production activities, resulting in a need for Class II disposal wells in some areas previously considered unproductive.

Recently, a number of small to moderate magnitude (M<5.0) earthquakes[1] have been recorded in areas with Class II disposal wells related to shale hydrocarbon production. To address the concern that induced seismicity could interfere with containment of injected fluids and endanger drinking water sources, EPA's Drinking Water Protection Division requested that the UIC National Technical Workgroup (NTW) develop a report with practical tools to help UIC regulators address injection-induced seismicity. The Induced Seismicity Working Group (WG) of the NTW developed this report in response, using the existing Class II regulatory framework to provide possible strategies for managing and minimizing the potential for significant injection-induced seismic events.[2] The report focuses on Class II disposal operations and not enhanced recovery wells or hydraulically fractured wells. In formulating the strategies in this report, the NTW conducted a technical literature search and review. Additionally, the NTW evaluated four case examples (in Arkansas, Ohio, Texas, and West Virginia) and considered data availability and variations in geology and reservoir characteristics.

Unconventional production activities and associated larger wastewater volumes have resulted in an increased need for disposal capacity. Some disposal wells handling the increased volumes are located in geographic areas where disposal has not previously occurred. A growing number of disposal wells, some of which are in these new geographic areas, have been suspected of inducing seismicity. Of the approximately 30,000 Class II disposal wells in the United States, very

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[1] Information on earthquake terms is included under Glossary Terms In the full report or at http://earthquake.usgs.gov/learn/glossary/ for general earthquake terms

[2] For the purposes of this report, the Induced Seismicity Working Group considers "significant" seismic events to be those of a magnitude that could potentially cause damage to or endanger underground sources of drinking water.

few disposal well sites have produced seismic events with magnitudes greater than M4.0.[3] In addition, EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity.

Disposal wells are one of a number of historic causes of human activity-induced earthquakes. Others include construction and management of dams and water reservoirs, mining activities, oil and gas production, and geothermal energy production. Evaluation of induced seismicity is not new to the UIC program. The first comprehensive study was completed for the EPA Office of Water over 25 years ago, (Wesson and Nicholson, 1987[4]; finalized as Nicholson and Wesson, 1990). This report is intended to describe for UIC program management the current understanding of induced seismicity within the existing Class II regulatory framework for Class II disposal. The Class II UIC program does not have regulations specific to seismicity but includes discretionary authority that allows additional conditions to be added to the injection permit on a case-by-case basis, along with additional requirements for construction, corrective action, operation, monitoring, or reporting (including closure of the injection well) as necessary to protect USDWs.[5] Legal and policy considerations of Class II regulations, including regulatory revisions, are outside the scope of this technical report. This report is not a guidance document and does not provide specific procedures, but it does provide the UIC Director with considerations for addressing induced seismicity on a site-specific basis, using Director discretionary authority.

The NTW confirmed the following components are necessary for significant injection-induced seismicity: (1) sufficient pressure buildup from disposal activities, (2) Faults of Concern,[6] and (3) a pathway allowing the increased pressure to communicate with the fault. The NTW noted that no single recommendation addresses all of the complexities related to injection-induced seismicity, which is dependent on a combination of site geology, geophysical and reservoir characteristics. An absence of historical seismic events in the vicinity of a disposal well does not provide complete assurance that induced seismicity will not occur; however, this historic absence

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[3] National Research Council. Chapter 3, Table 3.4, page 104, and Chapter 7, injection wells for the disposal of water associated with energy extraction finding no. 1, *in* Induced seismicity potential in energy technologies. (Washington, DC: The National Academies Press, 2013), 104 and 171–172.

[4] R.L. Wesson and C. Nicholson, Earthquake hazard associated with deep well injection: A report to the U.S. Environmental Protection Agency, U.S. Geological Survey Open-file Report 87-331, 1987, 108 pp.

[5] 40 CFR §144.12(b); 40 CFR §144.52(a)(9) or (b)(1); or appropriate section of 40 CFR Part 147

[6] A Fault of Concern is a fault optimally oriented for movement and located in a critically stressed region. The fault is also of sufficient size and possesses sufficient accumulated stress / strain, such that fault slip and movement has the potential to cause a significant earthquake. Fault may refer to a single fault or a zone of multiple faults and fractures. See also Geologic Stress Considerations later in this document; APPENDIX B: Site Assessment Considerations for Evaluating Seismicity; and APPENDIX M: State of Stress for more complete discussion.

may be one indicator of induced seismicity if seismic events occur following activation of an injection well. Such a conclusion is based on the assumption that a reliable history of seismic monitoring in the region of the injection well exists. However, the accuracy of such monitoring depends on the robustness of the seismic monitoring network for any given area, along with consideration for how long such a network has been in place. Conclusive proof of induced seismicity is difficult to demonstrate but is not a prerequisite for taking early prudent action to address the possibility of induced seismicity.

The NTW developed a decision model (Figure 1) to inform UIC regulators about site assessment strategies and practical approaches for assessing the three fundamental components. The model begins with considerations for a site assessment dependent on location-specific conditions, because understanding the geologic characteristics of a site is an essential step in evaluating the potential for injection-induced seismicity. Monitoring, operational and management approaches with useful practical tools for managing and minimizing suspected injection-induced seismicity are recommended.

During its review, the NTW also found that the application of basic petroleum engineering practices coupled with geology and geophysical information can provide a better understanding of reservoir and fault characteristics. The multidisciplinary approach offers many ways of analyzing injection-induced seismicity concerns, possibly identifying anomalies that warrant additional site assessment or monitoring. Such an approach would be enhanced by collaborative work between a wide variety of individuals in industry, government, and scientific and engineering research organizations. Consequently, the NTW recommends that future research consider a practical multidisciplinary approach coupled with a holistic assessment addressing disposal well and reservoir behavior, geology, seismology and other appropriate specialty fields of study.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) program, authorized by the Safe Drinking Water Act, regulates injection of fluids related to oil and gas production into Class II wells, for the protection of underground sources of drinking water (USDW). There are approximately 30,000 Class II active disposal wells in the United States used to dispose of oil and gas related wastes, many of which have operated for decades. EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity.[7] Very few of these disposal well sites have produced seismic events with magnitudes[8] greater than M4.0[9]. For example, at the time of this report, there were approximately 2,700 active disposals wells in Louisiana, with no recent significant[10] seismic events occurring as a result of the disposal activities. However, unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have increased oil and gas production activities, resulting in a need for new Class II disposal wells in expanded geographic areas.

Disposal wells are just one of a number of historic causes of human activity-induced earthquakes.[11] Other causes may include construction and management of dams and water reservoirs, erection of skyscrapers, mining activities, oil and gas production, geothermal energy production and geologic carbon sequestration.

ENHANCED RECOVERY INJECTION WELLS

Class II injection wells include injection wells used for enhanced recovery as well as those used for oil and gas production wastewater disposal. Injection for enhanced recovery projects generally poses less potential to induce seismicity than wastewater disposal because pressure increases resulting from injection for enhanced recovery are partially offset by nearby production wells. Disposal wells have no offsetting withdrawal and therefore, have a greater potential for pressure buildup. Given the recent seismic activity associated with Class II disposal wells, this report focuses on recommendations to manage or minimize induced seismicity associated with these wells.

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[7] Seismic events resulting from human activities are referred to as induced, for this report.

[8] Magnitude will refer to the values reported by the USGS Advanced National Seismic System catalog.

[9] Chapter 3, Table 3.4, page 104, and Chapter 7, Injection Wells for the Disposal of Water Associated with Energy Extraction Finding No. 1, pages 171-172; "Induced Seismicity Potential in Energy Technologies," 2013 NAS Publication.

[10] For the purposes of this report, "significant" seismic events are of a magnitude that has the potential to cause damage or endanger underground sources of drinking water or cause infrastructure damage.

[11] Earthquake terms are included under *Glossary Terms* later in this report or http://earthquake.usgs.gov/learn/glossary/ for general earthquake terms.

Hydraulic Fracturing

Although not the emphasis of this effort, seismicity associated with hydraulic fracturing (HF) was addressed by a review of selected literature sources. HF has a low likelihood of inducing significant seismicity, for reasons explained below.

Unlike wastewater disposal wells where injection occurs for an extended period of time, HF is a short-term event designed to create cracks or permeable avenues in lower permeability hydrocarbon-bearing formations. HF activity is followed by the extraction of reservoir fluids and a decrease in pressure within the formation. Therefore, the "pressure footprint" of a well that has been hydraulically fractured is typically limited to the fracture growth or fracture propagation area (Gidley et al., 1990). In comparison, the "pressure footprint" of an injection well is related to the injection rate, duration of the injection period and transmissibility of the reservoir (Lee et al., 2003). Class II disposal wells typically inject for months or years and generate large "pressure footprints" with no offset production of fluids.

HF is designed to crack the formation to enhance production. Several studies have documented microseismicity (M<1) caused by HF (Das and Zoback, 2011; Phillips et al., 2002; Warpinski, 2009; and Warpinski et al., 2012). Studies have also documented numerous examples of small faults encountered during the HF process with microseismicity where magnitudes are below M0 (Maxwell et al., 2011; Warpinski et al., 2008). Recording these very low magnitude seismic events requires the use of downhole seismometers in nearby wells (Warpinski, 2009). Though rare, felt HF-induced seismicity is possible if the HF encounters a Fault of Concern.[12] Documented cases list seismic events up to M3.8 caused by HF communication with Faults of Concern (British Columbia Oil and Gas Commission, 2012; de Pater and Baisch, 2011; Holland, 2011 and 2013; Kanamori and Hauksson, 1992).

Geothermal Injection Wells

A number of informative references exist on induced seismicity and enhanced geothermal systems. These references cover a broad range of seismicity issues and outline many avenues of additional research needed (Hunt and Morelli, 2006; Majer et al., 2007 and 2011). These authors documented the combination of monitoring techniques with adjustment of operational parameters to control seismicity. For example, thermal stress, in addition to pressure buildup, plays a key role in geothermal seismicity and may be applicable to wastewater disposal wells,

[12]A Fault of Concern is a fault optimally oriented for movement and located in a critically stressed region. The fault is also of sufficient size, and possesses sufficient accumulated stress/strain, such that fault slip and movement has the potential to cause a significant earthquake. Fault may refer to a single fault or a zone of multiple faults and fractures.

depending on the temperature of the injected fluids and receiving formation (Perkins and Gonzalez, 1984).

CO_2 Geologic Sequestration

Geologic sequestration of CO_2 requires a Class VI UIC permit. The Class VI permitting process includes assessment of potential induced seismicity. Class VI regulations require a detailed review on a site-specific basis; consequently, Class VI wells were not considered in this report. Some research pertaining to potential seismicity from CO_2 geologic sequestration may be applicable to wastewater disposal.

Directive and Working Group

Revisions to Class II regulations are outside the scope of this technical report. This report is not a policy or guidance document and does not provide an exhaustive list of specific permitting procedures. It provides the UIC Director with considerations for minimizing and managing induced seismicity on a site-specific basis, using Director discretionary authority.

To address the concern that injection-induced seismicity could cause a breach in the containment of injected fluids and endanger drinking water sources, EPA's Office of Ground Water and Drinking Water (OGWDW) Drinking Water Protection Division requested that the UIC National Technical Workgroup (NTW) develop recommendations for consideration by UIC regulators (APPENDIX A). The UIC NTW consists of UIC staff from each EPA regional office, EPA headquarters, and six state UIC program representatives. The Injection-Induced Seismicity Working Group (WG) of the NTW was formed in June 2011 to spearhead development of a report recommending possible strategies for managing or minimizing significant seismic events associated with induced seismicity in the context of Class II disposal well operations. The WG was comprised of a subset of NTW members and members outside the NTW included for their expertise on the subject matter. A list of the WG members is provided later in this report. Drafts of the report were written by the WG, and finalized based on review by the NTW. Ultimately, the report is a product of the NTW.

Regulatory Authorities

This report describes, for UIC regulators, the current understanding of induced seismicity within the existing Class II regulatory framework for Class II disposal. Evaluation of induced seismicity is not new to the UIC program. Some UIC well classes address seismicity with specific regulatory requirements.[13] The Class II UIC program does not have regulations specific to seismicity but

[13] 40 CFR §146.62(b)(1) and §146.68(f) for Class I hazardous; §146.82(a)(3)(v) for Class VI geologic sequestration

rather includes discretionary authority that allows additional conditions to be added to the UIC permit on a case-by-case basis. Examples of this discretionary authority include additional requirements for construction, corrective action, operation, monitoring or reporting; (including well closure) as necessary to protect USDWs.[14] In the included case studies, the UIC Directors used discretionary authority to manage and minimize seismic events.

Potential USDW risks from seismic events could include loss of disposal well mechanical integrity, impact to various types of existing wells, changes in USDW water level or turbidity, USDW contamination from a direct communication with the fault inducing seismicity, or contamination from earthquake-damaged surface sources. However, EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity.

Report Purpose

The NTW's task was not to determine if there was a linkage between disposal and seismicity, but if a linkage was suspected, to identify practical approaches the UIC Director may use to minimize and manage injection-induced seismicity. A decision model was developed, which compiles and describes available options and illustrates a process for applying them to manage or minimize possible injection-induced seismicity. The site assessment considerations included in the model were those identified as pertinent by the WG, though other factors may also be appropriate depending on site-specific situations. The decision model also provides operational and monitoring options for managing injection-induced seismicity. It is supported by an extensive literature review and four case histories, which considered earthquake history, proximity of disposal wells to these events, and disposal well behavior.

Many of the recommendations and approaches discussed in this report may be applicable to other well classes. For example, disposal activities also occur in Class I hazardous and non-hazardous wells, various Class V wells, and Class VI wells. The U.S. Department of Energy and the International Energy Agency (IEA) have authored several publications dealing with specific Class V geothermal seismicity issues. The WG reviewed a number of publications as part of the literature survey for this report (APPENDIX K). Conclusions from some of these reports apply to this Class II injection-induced seismicity project and are referenced within the body of the report.

Injection-Induced Seismicity Project Objectives

The WG analyzed existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

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[14] 40 CFR §144.12(b); 40 CFR §144.52(a)(9) or (b)(1); or appropriate section of 40 CFR Part 147

1. What parameters are most relevant to screening for injection-induced seismicity?
2. Which siting, operating or other technical parameters are collected under current regulations?
3. What measurement tools or databases are available that may be used to screen existing or proposed Class II disposal well sites for possible injection-induced seismic activity?
4. What other information would be useful for enhancing a decision-making model?
5. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection-induced seismicity?
6. What lessons have been learned from evaluating case histories?

Working Group Tasks

The UIC NTW was tasked by UIC management with developing a report including technical recommendations to manage or minimize significant levels of injection-induced seismicity.

The UIC NTW utilized the following to address the objectives:

1. Compare parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Prepare a decision model
3. Assess applicability of pressure transient testing and/or pressure monitoring techniques
4. Summarize lessons learned from case studies
5. Recommend measurements or monitoring techniques for higher risk areas
6. Analyze applicability of conclusions to other well classes
7. Recommend specific areas for further research needed

Working Group Approach

The WG adopted the following strategy:

1. Summarize geoscience factors and applications
2. Apply petroleum engineering methods
3. Compile and review historical and current scientific literature, including ongoing projects and material associated with upcoming reports on injection-induced seismicity
4. Select and study case examples of Class II brine disposal wells suspected of inducing seismicity and provide a summary of lessons learned for the following areas:
    a. North Texas
    b. Central Arkansas
    c. Braxton County, West Virginia
    d. Youngstown, Ohio

A study of disposal wells in areas with no seismic activity was not performed.

5. Develop a decision model
6. Consult with the U.S. Geological Survey (USGS) seismologists on the potential for using deep stress field measurements and the USGS earthquake information as screening tools (APPENDIX M:)
7. Compare data collected under existing UIC requirements to relevant information needed for assessment of injection-induced seismicity
8. Solicit review by EPA's UIC NTW and subject matter contributors from state agencies, academia, researchers and industry.

Review Process

As noted above, prior to submission to the NTW, the draft report was sent for review to specific subject matter experts and corrections made accordingly. After the NTW passed the report to OGWDW, it was decided to conduct an additional independent peer review.

Peer Review

The OGWDW engaged one of its contractors to facilitate and coordinate an external review of the NTW report. In the process of developing the contract, OGWDW also developed charge questions to guide the reviewers in the areas of desired feedback. With guidance from EPA, the contractor developed a ranked list of about 20 experts. Six reviewers were selected from that list (Table 1), based on their qualifications, including experience with injection-induced seismicity.

TABLE 1: SELECTED PEER REVIEWERS

Peer Reviewer	Jeff Bull	Robin McGuire	Craig Nicholson	Kris Nygaard	Heather Savage	Ed Steele
Affiliation	Oil/Gas Industry	Consultant	Academia	Oil/Gas Industry	Academic Laboratory	Oil/Gas Industry and Consultant
Organization	Chesapeake Energy Corporation	Lettis Consultants International, Inc.	University of California, Santa Barbara	ExxonMobil	Lamont-Doherty Earth Observatory, Columbia University	Swift Worldwide Services
Professional Years	30+	30+	30+	20+	10+	40+

Peer Review Charge

The reviewers were asked to focus on four charge questions during their review and to provide expert advice and recommendations on these questions, in addition to providing general comments. The four charge questions, developed by EPA, were as follows:

Basic Mechanism of Injection-Induced Seismicity

The NTW identified three key components contributing to injection-induced seismicity: (1) the presence of a stressed fault, (2) pressure buildup from disposal operations, and (3) a pathway for the increased pressure to communicate from the disposal well to the fault. Do these three key elements capture the causal relationship of disposal-induced seismicity? Please comment on other elements relating induced seismicity to Class II disposal injection that might be useful to consider when developing strategies to minimize or manage injection-induced seismicity.

Variety and Validity of Approaches

The NTW identified site assessment considerations along with monitoring and operational approaches for assessing the three key components contributing to injection-induced seismicity. Please comment on the appropriateness of the site assessment considerations identified for assessing the potential for induced seismicity. What other site assessment considerations might be considered? Are the monitoring and operational approaches identified appropriate for minimizing or managing injection-induced seismicity? Are there additional considerations that might be considered to address the key elements contributing to injection-induced seismicity?

Reservoir Engineering Analysis Application

The NTW sought to expand the review of the pressure buildup and pathway components of induced seismicity beyond geosciences. The NTW integrated reservoir engineering analysis into the evaluation of the potential relationship between Class II injection activity and seismicity by using data that is already collected by owners and operators as well as standard evaluation techniques employed in the oil and gas industry. Is the reservoir engineering analysis suggested by the NTW reasonable for identifying anomalies in an effort to minimize or manage injection-induced seismicity? Please identify other analyses (including the type of data needed and benefits and disadvantages of their use) that might be useful for evaluating reservoir behavior during Class II disposal injection.

Recommended Future Efforts for the EPA

Please identify any additional key literature or other data sources that might be useful to ensure a comprehensive understanding of the potential for induced seismicity in the context of Class II disposal wells.

Final Peer Review Follow-up

Once all of the comments were received, the OGWDW requested help in assessing the comments.

The comment review team (team) consisted of EPA Region 6 staff, the past NTW chair and two representatives of OGWDW. The team assessed the comments and divided them into three categories described below; it also developed a strategy to re-engage the NTW for a final review of the report, once updated based on the peer review comments.

The team assessed and tabulated the peer reviewers' comments (APPENDIX N:) according to the relevant section of the report and the commenter. The team then classified each of the comments according to the following categories:

1. Comments requiring no response: These are typically statements or opinions by the commenter.
2. Comments relevant to the topic, but outside the scope of the project: These comments are addressed in more detail in APPENDIX A. This category of comments was grouped according to the nature of the comment, as described below.
    a. Authority: Comments related to the applicability of EPA authority.
    b. Scope: Comments outside the purpose of the report (providing a practical UIC management tool) including recommendations for policy changes, new

regulations, extensive research or additional studies, such as complex proprietary modeling.

   c. Clarify: Comments relevant to the topic that were addressed by directing the commenter to the appropriate place in the report or by providing additional UIC program background information.

3. Comments relevant to the topic and within the scope of the project. These comments required revisions to the document.

Additional decisions included the following:

- The original cut-off date for inclusion of case studies (September 2013) was maintained.
- A separate list of the peer reviewers' recommended references was added to APPENDIX K: Subject Bibliography, excluding non-peer-reviewed articles.
- A new appendix was created to provide responses to all comments grouped in Category 2 (above).
- The following areas were outside the scope of the project and were not incorporated:
    - Adoption of a formal comprehensive risk assessment
    - Specific policy or regulatory requirements
    - Ongoing research, modeling or simulations
    - Basic UIC program discussions

Geoscience Factors Related to Injection-Induced Seismicity

The following paragraphs provide a general overview of the various geoscience aspects relevant to injection-induced seismicity. 0 describes these aspects in greater detail. The three key characteristics related to potential injection-induced seismicity that may lead to fault slippage and associated earthquakes are: (1) an increase in the formation pore pressure from disposal activities; (2) a fault (or zone of multiple faults and fractures) optimally oriented for movement, located in a critically stressed region, of sufficient size, and possessing sufficient accumulated stress/strain, such that fault slip and movement would have the potential to cause a significant earthquake (Fault of Concern); and (3) a permeable avenue (matrix or fracture permeability) allowing the pore pressure increase to reach the fault.

Background

In general, continental oil and gas deposits occur in sedimentary rocks deposited by ancient seas over granitic basement rocks. Basement rocks have been and continue to be subjected to ongoing global tectonic forces. These forces result in fracturing and faulting (fracturing with lateral displacement) and are the origin of the constantly stressed condition of continental basement rocks. Nearly all early cases of suspected injection-induced seismicity felt by humans

have involved communication between disposal zones and basement faults. For these reasons, geologic site assessments related to potential injection-induced seismicity should include an analysis of both faults and stress conditions in basement rocks of the disposal well area. Since subsurface geologic stresses are transferred over great distances, fault and stress analyses should encompass a regional area around the disposal well.

Geologic Stress Considerations

Historic seismic activity is an indicator of critical stress in basement rocks. Subsurface stresses are typically not uniform in every direction. The orientation of faults with respect to the principal stresses is a fundamental indicator of which faults are subject to activation from pore pressure increases. Not all faults are Faults of Concern, only those optimally oriented in the subsurface stress field such that an increase in pore pressure can induce movement. Optimal orientation of faults is described in greater detail by Holland (2013). Unfortunately, the principal stress direction may not be readily known to injection well permitting authorities. Some options to help determine the principal stress direction include data on borehole geometry, the World Stress Map (APPENDIX M: Task 2; Tingay et al., 2006), or consultation with experts, such as state geological surveys or universities. These experts may provide an estimate of the principal stress direction for a particular area as well as information on the location and orientation of known faults in the area.

An additional resource is the Quaternary Fold and Fault Map created by a USGS consortium (APPENDIX M: Task 1). This map shows all active faults with surface expression that are known to have created earthquakes over M6.0. These faults were defined from the geologic record for the Quaternary age (the last 1.6 million years).

Geophysical Data

Across the United States, the USGS funds or maintains seismic arrays and associated databases that are excellent web-based resources for seismic history assessments. A summary of available databases is provided in APPENDIX L: . Seismometers in the permanent monitor grid in most of the central and eastern continental United States are spaced up to 200 miles (300 km) apart. With this spacing, the system is capable of measuring events down to approximately M3.0 or M3.5, although in some areas measurement capabilities may extend down to a M2.5. Hypocenter location error for the permanent array averages up to 6 miles (10 km) horizontally and 10,000 to 16,500 feet (3–5 km) vertically. In tectonically active areas such as the continental western margin and New Madrid Seismic Zone, the seismometer spacing is closer, resulting in more accurate earthquake locations (hypocenter by latitude, longitude and depth). Additionally, closer grid spacing generally allows measurement of seismic events of smaller magnitude. Despite the accuracy limitations, USGS or other seismicity databases described in APPENDIX L:

and APPENDIX M: are useful tools for initial site assessments. Event information included in databases is periodically updated over time as data are reprocessed. Relocated events are found in later publications and may not be in the seismicity databases.

Communication with Basement Rock

In almost all historic cases, felt injection-induced seismicity was the result of direct injection into basement rocks or injection into overlying formations with permeable avenues of communication with basement rocks. Therefore, the vertical distance between an injection formation and basement rock, as well as the nature of confining strata below the injection zone, are key components of any assessment of injection-induced seismicity. In areas of complex structural history, strata beneath the injection zone may have compromised vertical confining capability due to natural fracturing. Also, faulting in basement rock can extend into overlying sedimentary strata, thus providing direct communication between the disposal zone and the basement rock.

Importance of Porosity and Permeability of Injection Strata

Stratigraphic formations used as disposal zones can have a complex range of porosity types and permeability values. For this report, two fundamental types of porosity are considered; matrix porosity and fracture porosity. Matrix porosity refers to the rock pore spaces, whether formed during deposition or alteration following deposition. Natural fractures in rocks create a second type of porosity referred to as fracture porosity. Fractures can provide preferential flow paths for fluid flow (permeability). Matrix porosity generally is characterized by smaller interconnections and less permeability than fractures, but high matrix porosity offers more storage space, potentially limiting the horizontal extent of pressure distribution. Pressure buildup is more difficult to predict in naturally fractured flow-dominated disposal zones and can extend much farther from the injection well. Most of the case study wells suspected of injection-induced seismicity in this report involved naturally fractured disposal zones.

Petroleum Engineering Applications for Evaluating Induced Seismicity

Petroleum engineering applications have been used for decades in the oil and gas industry to evaluate wells and enhance hydrocarbon production. Petroleum engineering methodologies used in this document adhere to practices and equations commonly presented in petroleum engineering literature. The review of recent injection-induced seismicity literature revealed a lack of a multidisciplinary approach inclusive of petroleum engineering techniques. Additionally, typical Class II disposal permit reviews do not use many of the petroleum engineering analyses available, but such techniques could be useful in evaluating the potential for injection-induced seismicity.

Petroleum engineering methodologies provide practical tools for evaluating the three key components that must all be present for induced seismicity to occur: (1) sufficient pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway allowing the increased pressure to communicate from the disposal well to the fault. Different well and reservoir aspects can be evaluated depending on the methods used. Specifically, petroleum engineering methods typically focus on the potential for reservoir pressure buildup and the reservoir flow pathways present around a well and at a distance, and characterize reservoir behavior during the well's operation. Petroleum engineering approaches enhance geological and seismological interpretations related to the characterization of faults and flow behavior. Some of the case study wells reviewed exhibited specific Hall integral and derivative responses (described further below and in APPENDIX D:) that corresponded to area seismic events. The Hall integral and derivative responses at these wells suggest hydraulic communication with a boundary (i.e., an offset well or fault) at some unknown distance from the well.

The petroleum engineering approach incorporates information typically collected from the permit application (well construction and completion data) and data on injection volumes and pressures reported for compliance purposes during operation of the well. This information is presented in a graphical format to illustrate behavior of the well over time. These graphs are compared to graphs of expected well behavior from various reservoir behavior models to identify anomalous patterns.

Review of operational data can provide a qualitative look at the well behavior. Operational analysis consists of plotting readily available data reported as part of the Class II disposal well permit compliance. These plots include:

- Injection volumes and wellhead pressures
- Bottomhole injection pressure gradient
- Hall integral and derivative

Plotting injection volumes and pressures in an appropriate format along with operating pressure gradients may highlight significant changes in disposal well behavior. The operating gradient plot can indicate whether a disposal well is operating above fracture gradient. The Hall integral and derivative plot utilizes operating data to characterize a well's long term hydraulic behavior by providing a long-term, long distance look into the disposal zone. For example, a decline in wellhead pressures coupled with an increase in volumes injected reflects enhanced injectivity (increased ease of injection), shown by the derivative dropping below the Hall integral, while the derivative trend rising above the integral represents increased injectivity. Changes in Hall integral and derivative trends can represent reservoir heterogeneities (i.e., faults, stratigraphic changes, etc.), changes in completion conditions, reservoir boundaries, and effects of offset wells. Details

concerning the application of both the operating gradient and Hall integral and derivative plots are discussed in APPENDIX D: . Both plot types are utilized in the four case studies detailed in Appendices E through H.

Supplemental evaluations may be performed but require data or logs that may or may not be routine for Class II disposal permit activities. These evaluations quantitatively assess potential pathways and potential reservoir pressure buildup and may include the following:

- Step rate tests
- Pressure falloff tests
- Production logs
- Static reservoir pressure measurements

Step rate tests are used to determine the formation parting pressure (fracture extension pressure). The quality of the data analysis is dependent on the amount of pressure data recorded during the test. Pressure falloff tests can provide the completion condition of the well (wellbore skin) and reservoir flow characteristics. Production logs typically include temperature logs, noise logs, radioactive tracer surveys, oxygen activation logs or spinner surveys. These types of logs are used to evaluate the fluid emplacement at the well. Periodic static pressure measurements provide an assessment of reservoir pressure buildup. More details on supplemental testing and engineering evaluations are included in APPENDIX D: .

Review of Scientific Literature

Literature Sources

Injection-induced seismicity has been documented in many reports dating from 1968 through 2013. The WG compiled and reviewed an extensive reference list included in APPENDIX K: . The primary resource was USGS Bulletin 1951 (Nicholson and Wesson, 1990).[15] Induced seismicity is a rapidly expanding area of research. This list is not a complete resource list. Inclusion of an article or website in APPENDIX K: does not reflect NTW's agreement with the conclusion of the article.

Earthquake Reporting

The USGS Advanced National Seismic System (ANSS) comprehensive catalog (ComCat), the largest U.S. database of earthquake events, includes earthquakes from the USGS National Earthquake Information Center (NEIC) and contributing networks. The real-time report and some

[15] An earlier draft version (available only in EPA files) was assumed to have been replaced by the final publication.

of the catalogs include the location accuracy of the event. Catalog details may vary, but are an important consideration for induced seismicity analyses. Earthquake catalogs are discussed more fully in APPENDIX L: and APPENDIX M: . USGS, state geologic agencies and universities may also collect and/or host earthquake information on their websites. There may be differences between databases in detection thresholds, as well as inconsistencies in calculated epicenters, depths or magnitudes for each earthquake. Databases may not cover the same geographic regions. It should be noted that the expansion or development of regional seismometer networks may allow measurements of seismic activity at a lower magnitude threshold than previously recorded, creating the appearance of increased seismicity. Event interpretation is discussed more fully in APPENDIX D: .

Possible Causes of Induced Seismicity

Seismicity induced by human activities has been extensively documented. Seismic events have been associated with mining, construction and management of dams and water reservoirs, geologic carbon sequestration, erection of skyscrapers, geothermal energy related injection, oil and gas production activities and disposal wells. Davis and Frohlich (1993), Nicholson and Wesson (1990, 1992), and Suckale (2009, 2010) studied case histories of potential oil- and gas-related induced seismicity across the United States and Canada. Several waste disposal case studies were investigated, including Rocky Mountain Arsenal and Paradox Valley in Colorado, and two locations in far northeastern Ohio (Ashtabula and Cleveland, occurring from 1986 to 2001). Opposing conclusions were drawn on whether the Ohio seismicity was related to injection (Seeber and Armbruster, 1993 and 2004; Gerrish and Nieto, 2003; Nicholson and Wesson, 1990). More recent publications concluded disposal activity induced seismicity in central Arkansas and Youngstown, Ohio (Horton, 2012; Horton and Ausbrooks, 2011; Holtkamp et al., 2013; Kim et al., 2012; Kim, 2013; ODNR, 2012). Disposal activities at the Rocky Mountain Arsenal, Paradox Valley and enhanced recovery at the Rangely Field, also in Colorado, have been associated with inducing seismicity. Operations at both Colorado facilities began prior to promulgation of federal UIC regulations. Production from the Rangely Field is ongoing.

Several studies concluded that the Rocky Mountain Arsenal seismicity was caused by injection (Davis and Frohlich, 1993; Nicholson and Wesson, 1990 and 1992; Suckale, 2009 and 2010). At the Rocky Mountain Arsenal, the largest three earthquakes, with magnitudes between M5.0 and M5.5, occurred over one year after injection stopped. In March 1962, injection of waste fluids from chemical manufacturing operations at the Rocky Mountain Arsenal was initiated into fractured crystalline basement rock beneath the facility. Initial injection exceeded the formation fracture pressure from March 1962 through September 1963, when the surface pump was removed, leaving injection to continue under hydrostatic pressure. Pumps were once again used for injection from April 1965 through February 1966, when injection ceased. Seismicity started

5 miles (8 km) from the well on April 24, 1962, ranging from M1.5 to M4.4 from 1962 through 1966, with three earthquakes ranging from M5.0 to M5.5 in 1967. Subsequent investigations identified a major fault near the well and showed a direct correlation between increases in bottomhole pressure during injection and the number of earthquakes, using rank difference correlation (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Raleigh, 1972).

From 1969 through 1974, the relationship between seismicity and enhanced recovery injection operations at the Rangely Field in Colorado was studied (Raleigh, 1972; Raleigh et al., 1976). Reservoir pressures were controlled by varying injection rates into enhanced recovery wells and withdrawal rates from production wells within the Rangely Field to determine the relationship between pressure and induced seismicity. Fourteen seismometers deployed throughout the area recorded events ranging from M-0.5 to M3.1, which occurred in clusters in both time and space. Most of these events were below the threshold that is typically felt by humans.[16] Seismometer data and injection pressure and volume data, coupled with modeling, confirmed that earthquakes were induced through an increase in pore pressure. Frictional strength along the fault varied directly with the difference between total normal stress and fluid pressure (Raleigh et al., 1976). Unusual features in this case included measurable response to fluid pressure along one part of the fault, recordable compartmentalization within the reservoir around the fault, and verification that maintaining the reservoir pressure below a calculated threshold stopped the seismicity (Raleigh, 1972; Raleigh et al., 1976). The Rangely Field example illustrates how operational changes can be used to mitigate induced seismicity.

Numerous earthquakes were induced by Class V disposal operations in Paradox Valley, Colorado (Ake et al., 2002 and 2005; Block, 2011; and Mahrer et al., 2005). Seismicity is being managed using intermittent injection periods, injection rate control and extensive seismic monitoring. Additionally, a proposed second Class V disposal well located several miles from the existing well is being evaluated by the U.S. Bureau of Reclamation in response to an expanding area of seismicity. The existing well is required for salinity control for the Delores River and operates above fracture pressure. More information is included in APPENDIX J: .

Disposal wells have been suspected of inducing seismicity in a number of recent cases (USGS, 2013). Verifying the presence of alternative causes of seismicity, such as unusual changes in lake level (Holland et al., 2013; Klose, 2013; El Hariri et al., 2010), is a useful scientific approach.

[16] Microseismic and small seismic events may occur but go undetected or unfelt and pose no significant risk to human health or USDWs.

Determinations of Injection-Induced Seismicity

Nicholson and Wesson (1990) stated that induced seismicity determinations rely on three primary characteristics of earthquake activity:

1. Geographic association between the injection zone and the location of the earthquake
2. Exceedance of theoretical friction threshold for fault slippage
3. Disparity between previous natural seismicity and subsequent earthquakes following disposal with elevated pressures

Davis and Frohlich (1993) developed a practical approach for evaluating whether seismic events were induced by injection based on characteristics similar to those stated by Nicholson and Wesson (1990), e.g., history of previous seismic events, proximity in time and space and comparison of critical fluid pressures. The Davis and Frohlich approach utilizes a series of fundamental questions to evaluate the likelihood of induced seismicity. These questions are outlined below:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicenters near wells (within 3 miles or 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressure at hypocenter locations sufficient to encourage seismicity?

Although these approaches are qualitative and do not result in positive proof of injection-induced seismicity, they may be useful to UIC regulators as preliminary screening tools. Evaluating causality requires analysis of all important natural and anthropogenic triggers that can disrupt the subsurface stress regimes in proximity to faults in the local area. As such, proof of induced seismicity is difficult to achieve and may be time-consuming but is not a prerequisite for taking early prudent action to address the possibility of induced seismicity.

Note that petroleum engineering techniques used in analysis of oil and gas development were not typically used to evaluate reservoir characteristics potentially associated with induced seismicity in the scientific literature reviewed for this report.

Case Study Results

The WG task was to provide practical tools that the UIC Director could use to assess site conditions prior to developing a plan to minimize and manage seismicity. Case study efforts were directed toward assessments of typical UIC program compliance data and its usability for

characterization of injection well behavior and possible correlation with area seismicity. The case studies were not intended to focus on site problems or program administration issues, but rather to determine if practical assessment tools could be developed. The WG also found no indication that the injection wells associated with the case study areas injected outside of the operational boundaries or designated injection zones established by the permit parameters or endangered a USDW.

A total of four geographic areas of suspected injection-induced seismicity were selected by the WG for more detailed evaluation. These case studies were selected from areas where disposal wells were suspected to have caused recent seismic events. Initially, the north Texas, central Arkansas, and Braxton County, West Virginia, areas were selected. The Youngstown, Ohio, area was included later in the project because a disposal well was the suspected cause of a series of seismic events in late 2011. No cases were evaluated where injection-induced seismicity was not suspected.

Initially, the WG identified disposal wells located in the vicinity of recent seismic events in the selected geographic areas. In order to compare well activities to seismic events, a focus area based on a defined radius around the well was used to gather seismic data. Historic seismic events for the cases were derived from six different database catalogs. These external databases are discussed in more detail in APPENDIX L: . A radius of between 5 and 12 miles (8 to 19 km) around each case study well was selected based on the spacing density of the existing seismometers and location of the seismicity in the immediate area of the well. Additionally, there is uncertainty regarding the depth to the hypocenter.

The specific strategies used by the WG for evaluating the cases included engaging researchers who had studied two of the cases, reviewing available geologic structure maps, acquiring specific injection well data from the four state regulatory agencies and communicating with a well operator. A petroleum engineering analysis, based on the collected well data, was also performed on each case study well. Additional geoscience background and the results of EPA's petroleum engineering analysis on these cases are discussed in greater detail in the appendix specific to each case study (APPENDIX E, APPENDIX F: , APPENDIX G: , and APPENDIX H:).

Each case is discussed below through a background summary of the seismic activity and a description of how the case was evaluated by the WG. A summary of the common characteristics and lessons learned from the case studies is included following the case study summaries.

North Texas Area

Several small earthquakes occurred in the central part of the Dallas-Fort Worth metroplex near the Dallas-Fort Worth (DFW) International Airport on October 31, 2008, and near the town of

Cleburne on June 2, 2009. Both areas are located in north central Texas, in the eastern portion of the Barnett shale play. Prior to 2008, no earthquakes had been reported within 40 miles (64 km) of the DFW and Cleburne case study areas. Although Barnett shale hydrocarbons were discovered in Wise County in 1981, extensive drilling into the Barnett shale began only in the late 1990s with the advancement of horizontal drilling and well completion technologies. Disposal wells are the primary management approach for handling the wastewater associated with increased drilling activities. As of January 23, 2012, there were 195 UIC permits for commercial disposal wells in the 24-county area, only 2 of which were permitted in 2012, and not all of which were active.[17]

The Railroad Commission of Texas (RRC) standard UIC permit application package incorporates some site data and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs (Johnson, 2011). Site documentation reviewed by the WG included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state include well specifics (e.g., casing, cement information, perforations, and completion information) and disposal conditions (e.g., disposal zone, maximum allowable injection rate and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review of the annual injection reports indicated that the study area wells operated within the permitted pressure limits. One of the Cleburne area disposal wells was dually permitted as a Class II and Class I disposal well by different regulatory agencies. UIC Class I well requirements include conducting annual falloff tests. These tests provided reservoir characteristics and pressures for compliance with the Class I well permit and were not required in response to area seismicity. The WG reviewed the available falloff tests that confirmed the Ellenburger disposal interval was naturally fractured.

Following the 2008 and 2009 events, the RRC identified active disposal wells in the area for further evaluation due to the wells' proximity to the epicenters of seismic events and the absence of seismicity prior to initiation of disposal. RRC opened a dialogue with the operators of the suspect disposal wells, resulting in the voluntary cessation of injection for two wells, one in the DFW area and one in the Cleburne area, in August 2009 and July 2009, respectively. Since the two wells were shut-in, the frequency of seismic events in the immediate focus area, as reported by the USGS website, has substantially decreased.

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[17] RRC of TX website: http://www.rrc.state.tx.us/oil-gas/major-oil-gas-formations/barnett-shale-information/

The RRC subsequently reviewed its permit actions for these wells and other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify there were no resulting public safety issues from these events. In follow-up, the RRC consulted with industry representatives, along with researchers at the Texas Bureau of Economic Geology, Southern Methodist University and Texas A&M University. The RRC continues to monitor developments and research related to injection-induced seismicity.

However, later seismic activity in the DFW area was reported in Janská and Eisner (2012) and new episodic seismic events have occurred in other areas around Cleburne since the initial case study. Reviewing the multidisciplinary findings, available WG flow analysis supports cyclic radial flow followed by linear, fracture flow in the Ellenburger, a karstic carbonate disposal zone. There is a possibility that a few of the wells may have unintentionally created additional fracturing at the operating disposal pressures. Additionally, there appears to be a pattern of repeating cycles of decreased ability to inject followed by enhanced ease of injection, with the decreased injectivity corresponding to seismic events.

More details on this case study are available in APPENDIX E: .

Central Arkansas Area

From 2009 through 2011, a series of minor earthquakes occurred in the Fayetteville shale play near the towns of Guy and Greenbrier in Faulkner County, Arkansas. Regionally, the Enola area, located approximately 9 miles (14.5 km) southeast of Greenbrier, experienced a swarm of earthquakes starting in 1982 (Ausbrooks and Doerr, 2007).

The Arkansas Oil and Gas Commission (Commission) has members appointed by the governor of Arkansas. The Commissioners oversee the state oil and gas agency, also called the Arkansas Oil and Gas Commission (AOGC).

The AOGC standard UIC permit application package incorporates site assessment, well construction and completion information, along with other supporting documentation to demonstrate the protection of USDWs. Site assessment documentation includes surface maps, location plats, disposal depths, and inventory of offset wells within the area of review. Some permit applications contain detailed geologic information, such as a narrative, structure map, type log and additional interpretive data. Well construction details provided to the state include well specifics (e.g., casing, cement information, perforations, and completion information), and disposal conditions (e.g., disposal zone and maximum allowable injection rate and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. For one disposal well closest to the Enola area earthquakes, the AOGC also

requires pressure falloff testing, additional seismic monitoring and intermittent injection during the permitting process. WG review of the annual injection reports indicated that the Enola area well operated within the permitted pressure limits.

In October 2009, 3.5 months after injection commenced, earthquake activity began in the immediate Greenbrier area. To investigate the earthquakes, the AOGC worked with the Arkansas Geological Survey (AGS) and the University of Memphis Center for Earthquake Research and Information (CERI), and additional seismographs were deployed. In December 2010, following increased frequency and higher magnitude earthquakes, the Commission established a moratorium on the drilling of any new Class II disposal wells in an area surrounding the immediate vicinity of the increased seismic activity. The Commission also required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide hourly injection rates and pressures on a bi-weekly basis for a period of 6 months, through July 2011. During the moratorium period, the AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship.

In late February 2011, following a series of larger magnitude earthquakes, the operators of three disposal wells nearest to the seismic activity voluntarily terminated well operations prior to the issuance of the Commission cessation order issued on March 4, 2011. In July 2011, following the conclusion of the moratorium study, the Commission established a revised permanent moratorium area in which no additional Class II disposal wells would be drilled and required four of the original seven disposal wells to be plugged. The revised moratorium area was based on the trend of the Guy-Greenbrier fault, which the Commission determined as the probable cause of the seismic activity. The operators of three of the wells voluntarily agreed to plug the subject disposal wells and were consequently not parties to the July 2011 hearing heard by the Commissioners. Following the July 2011 Commission hearing, the AOGC issued an order to the operator of the fourth disposal well to plug that well. The order of the Commission issued in July 2011 became a final administrative regulation on February 17, 2012.

Since July of 2011, the AOGC, AGS and CERI continue to monitor disposal well operations and seismic activity. Additional seismic monitoring equipment has been purchased to facilitate the creation of an "early warning" system for emerging seismic activity, thereby allowing more time to develop appropriate responses.

Reviewing the multidisciplinary findings, operational data analysis indicated cycles of upward and downward shifts in both the Hall integral and derivative trends on the various plots for the four disposal wells with adequate monitoring history. As in other case studies, the upward shifts had at least some correspondence to area seismic events. The cyclic tandem plot patterns, when considered in conjunction with the area geology, embedded pressure transient tests, and the

operating gradient plots, likely reflect a combination of reservoir rock heterogeneities, fracturing occurrence in the wells in the form of enhanced injectivity, and interaction with reservoir boundaries such as a fault.

More details on this case study are available in APPENDIX F: .

Braxton County, West Virginia

In April 2010, a series of earthquakes ranging in magnitude from M2.2 to M3.4 began in Braxton County, West Virginia. This area had previously experienced a M2.5 earthquake in 2000. Braxton County is located on the eastern edge of the Marcellus shale play, and drilling in this area began in 2006. In March 2009, a nearby Class II disposal well began injecting Marcellus oil and gas production wastewater into the Marcellus formation.

The West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas standard UIC permit application package incorporates site assessment, well construction and completion information, along with other supporting documentation to demonstrate the protection of USDWs. The permit application for the well of concern contained detailed geologic information, such as an isopach and structure map. Site assessment documentation included surface maps, location plats, disposal depths, and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations and completion information) and disposal conditions (interval, rate and maximum pressure requested). The results of a step rate test were also included with the permit information. In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits. The data reported by the operator indicated that the well did not operate continuously.

In response to the seismic activity, the WVDEP reduced the maximum injection volume in September 2010. No additional earthquakes were recorded in the area after this restriction was enacted, until January 2012, when a M2.8 earthquake occurred. In response, the WVDEP further reduced the allowable monthly disposal volume by half the permitted value and researched the geologic structure of the area. The WVDEP and the WG found no conclusive evidence linking the cause of the seismicity to the disposal well.

In February 2012, WVDEP began requiring UIC permit applications to include detailed geologic information specifically to identify subsurface faults, fractures or potential seismically active features. This additional information requirement includes public or privately available geologic information, such as seismic survey lines, well records, published academic reports, government reports or publications, earthquake history, geologic maps or other like information to determine

the potential for injection to lead to activation of fault features and increase the likelihood of earthquakes.

Reviewing the multidisciplinary findings, operational analysis of the single disposal well injecting into the Marcellus shale indicates a hydraulic response. Based on the tandem plot analysis, a reservoir boundary (or boundaries) such as a fault, a pinch out, or possibly the limits of fracture stimulation (effectively the limits of permeable rock) was encountered.

More details on this case study are available in APPENDIX G: .

YOUNGSTOWN, OHIO

Starting on March 17, 2011, a series of 12 small magnitude seismic events occurred in Mahoning County in and around Youngstown, Ohio, culminating in a M4.0 event on December 31, 2011. Evidence suggested that the newly permitted, Northstar 1 Class II saltwater disposal well was the cause of the seismic activity, and the injection well was voluntarily shut down a day before the M4.0 event. The Northstar 1 injection well had been permitted as a deep stratigraphic test well and was drilled to a depth of 9,184 feet into the Precambrian basement rocks in April of 2010. On July 12, 2010, the Northstar 1 was issued a Class II saltwater disposal permit, and injection operations commenced on December 22, 2010.

The first Class II saltwater disposal well was permitted in Mahoning County in 1985, and eight more wells were converted to Class II injection between 1985 and 2004. These Class II injection wells utilized depleted oil and gas zones or were plugged back to shallower, non-oil or gas geologic formations for disposal. Injection was predominantly for disposal of production brine associated with conventional oil and gas operations. With the development of the unconventional shale plays in Pennsylvania and the lack of disposal in Pennsylvania, there was a need for additional disposal operations. To accommodate some of this need, five commercial disposal wells (Northstar 1 through 4, and 6) were permitted and drilled in Mahoning County, Ohio.

Historically, seismic monitoring in Ohio has been sporadic, and seismic events have not been accurately determined. In 1999, the Ohio Seismic Network (OSN) was established with 6 stations, and there were 24 seismic stations in operation in 2011. The seismometer at Youngstown State University was added to the OSN in 2003. Due to the continued seismic events occurring around the Youngstown area and near the Northstar 1 injection well, four portable seismic units were deployed on December 1, 2011, by Lamont-Doherty Earth Observatory. This portable array allowed more accurate identification of seismic events. After the M4.0 event on December 31, 2011, the governor of Ohio placed a moratorium on other deep injection wells within a 7 mile

radius of the Northstar 1 and put a hold on the issuance of any new Class II saltwater injection well permits until new regulations could be developed.

There is a seismically active zone in western Ohio and several episodically active faults 20 and 40 miles away from Youngstown (Baranoski, 2002 and 2013). Prior to the earthquakes recorded in 2011, the only known deep-seated fault was mapped approximately 20 miles (32 km) away from the seismic activity, based on a Pennsylvania Geological Survey report (Alexander et al., 2005). The vast majority of all historic and current seismic activity in Ohio occurs within the Precambrian basement rocks.

Due to the lack of deep geological information available for the Mahoning County area, a deep Precambrian basement fault in close proximity to the Northstar 1 went undetected. This fault was confirmed through evaluation of geophysical logs from the offset deep disposal wells and an interpreted seismic line.

According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio, Area* (Ohio Department of Natural Resources, 2012), data suggest seismicity in the Mahoning County area is related to Class II disposal. The Northstar 1 was drilled 200 feet into the Precambrian basement rock. The Ohio Department of Natural Resources (ODNR) report also suggests that pressure from disposal activities may have communicated with the Fault of Concern located in the Precambrian basement rock. The ODNR now prohibits the drilling of Class II injection wells into the Precambrian basement rock and has enhanced the standard UIC permit requirements[18] to facilitate better site assessment and collection of more comprehensive well information. The additional permit requirements include the following options 'as deemed necessary' and are reviewed on a well-by-well basis: pressure falloff testing, geologic investigation to identify faulting in the immediate vicinity of the well, a seismic monitoring plan or seismic survey, comprehensive suite of well logs, an initial bottomhole pressure measurement and a radioactive tracer or spinner survey. Additional operational controls[19] consist of: daily injection volume and pressure monitoring; an automatic shut-off system; and monthly monitoring of annular pressure.

In late 2012, ODNR also implemented a proactive approach to seismic monitoring around deep Class II disposal wells in Ohio and purchased nine portable seismic units to bolster earthquake monitoring capabilities. All nine portable seismic units are in operation, and ODNR has been monitoring these seismic stations in real-time since late 2012. Additionally, two disposal well

[18] http://codes.ohio.gov/oac/1501%3A9-3-06

[19] http://codes.ohio.gov/oac/1501%3A9-3-07

operators have installed their own portable seismic arrays around two new wells that ODNR is also monitoring in real-time.

Reviewing the multidisciplinary findings led to the following summary: the Northstar 1 injection well was completed into an approximately 900 foot openhole interval that crossed multiple formations, including faulted basement rock. A production log indicated flow likely occurred into an openhole interval above the basement rock; however, the entire completion interval was exposed to the well's operating pressure. The tandem plot indicated, as in the other case studies, several cycles of decreasing and increasing ease of injectivity, with some correspondence between seismic events, and a portion of the cycles displaying decreasing injectivity (Hall derivative upswings).

More details on this case study are available in APPENDIX H: .

Common Characteristics, Observations, and Lessons Learned From Case Studies

The case studies highlighted in this report provided important lessons and observations as well as common characteristics for wells suspected of inducing seismicity. The lessons learned provided a basis for the decision model as well as the approaches for minimizing and managing induced seismicity. The case study common characteristics and observations contributed to the site conditions component of the decision model. Common characteristics, coupled with key case study observations and the lessons learned, are summarized below.

Common Characteristics and Observations

The common characteristics and observations represent those aspects noted by the WG across multiple case studies.

- Petroleum engineering analysis indicated some correspondence between disposal well behavior and seismicity (all case study areas).
- The magnitude of the earthquakes may increase over time as observed in some case studies (central Arkansas, Ohio and West Virginia).
- Injection into fractured disposal zones directly overlying or connected to basement rock may be more vulnerable to injection-induced seismicity (Arkansas and Ohio case study areas).
- Deep disposal wells were in direct communication or suspected to be in hydraulic communication with basement rocks and Faults of Concern, as in the central Arkansas and Ohio examples. Disposal commonly occurred into disposal zones with naturally fractured reservoir characteristics, as in the central Arkansas and north Texas case study examples.

- Operational analysis of disposal rates and pressures on case study wells showed multiple incidences of repeating cycles of decreased ability to inject followed by enhanced ease of injection, with the decreased injectivity corresponding to seismic events (all case study areas).
- Operating wells below fracture pressure avoids or minimizes fracture propagation. Determination of appropriate operating conditions may require actual testing, such as a step rate test, to measure the formation parting pressure, or conducting an operational analysis for indication of enhanced injectivity.

Lessons Learned

The following key lessons were learned from the case study reviews:

- Initiating dialogue with operators can enhance cooperation, resulting in early voluntary action from operators, including well shut-in, or acquisition of additional site data.
    - Initiating dialogue between the operator and UIC regulator resulted in the voluntary shut-in of some suspect disposal wells (north Texas, central Arkansas and Ohio).
    - In two instances, an operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep-seated fault (north Texas and central Arkansas).
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone (all case study areas).
    - Hall integral and derivative plots may indicate a no-flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance.
    - Hall integral and derivative plots may illustrate enhanced ease or increased difficulty of injection.
- Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation, or encountering an increased permeability zone at distance (all case study areas).
- Acquisition of additional data may provide an improved analysis.
    - Additional site characterization may be beneficial:
        - Demonstrating a confining layer between the disposal zone and basement rock, and structural interpretation does not indicate faults extending into basement rock.
    - Increased recording of operational parameters can improve the quality of the operational data analysis.

        - Increased frequency of monitoring for permit parameters improved the operational analysis (central Arkansas and Ohio).
- Conducting a falloff test can further refine the reservoir characterization.
    - Fractured flow behavior was confirmed from the falloff test analyses for the Ellenburger disposal zone in a Cleburne area well (north Texas).
- Engaging external geophysical expertise may allow determination of a more accurate location (x,y,z) of the active fault and stress regime, through reinterpretation or increased seismic monitoring.
    - Especially useful when earthquake event magnitudes increased over time (central Arkansas, Ohio and West Virginia).
- Lack of historic seismic events may be a function of lack of seismic activity, seismic activity below recordable levels, or epicenters away from population centers.
- Existing seismic monitoring stations are generally insufficient to pinpoint active fault locations; more sensitive and better located monitoring systems are needed to accurately identify active faults and detect smaller events.
    - Installation of additional stations resulted in reliable identification of active fault locations (central Arkansas and DFW airport area of north Texas).
    - Epicenters of recorded events are scattered, due to an insufficient number of network stations in proximity to the activity (West Virginia).
- Seismic event data is periodically updated.
    - During preparation of this report the seismicity data were downloaded on different dates, with many of the initial events later revised or deleted.
        - Deletions typically occur between the first event report and entry into the catalog (NEIC or ComCat).
        - Revisions cover 3-D location as well as magnitude.
            - Several of the catalogs have added a revision date to their entries to help identify such changes.
- Seismic event data may be reprocessed, resulting in relocation of the event.
    - Fine-tuned relocation is possible when a sufficiently detailed velocity model is developed.
    - Relocated events are found in later publications and may not be in the catalogs.
- A multidisciplinary approach helped to minimize and manage induced seismicity at a given location (all case study areas).
    - State geological survey or university researchers provided expert consultation, facilitated installation of additional seismometers and provided a clearer understanding of the deep-seated active faulting (north Texas and central Arkansas).
- Director discretionary authority was used to solve individual site-specific concerns:

- Directors used authority to acquire additional site information, request action from operators and prohibit disposal operations. For example, directors used the following approaches:
    - Increased monitoring and reporting requirements for disposal well operators to provide additional operational data for reservoir analysis (central Arkansas).
    - Required one operator to install a seismic monitoring array prior to disposal as an initial permit condition (central Arkansas).
    - Plugged or temporarily shut-in suspect disposal wells linked to injection-induced seismicity while investigating or interpreting additional data (all case study areas).
    - Defined a moratorium area prohibiting Class II disposal wells in a defined high-risk area of seismic activity (central Arkansas).
    - Decreased allowable injection rates and total monthly volumes in response to seismic activity (West Virginia).

DECISION MODEL

The primary objective of the WG was to develop a practical tool, the decision model, for the UIC Director to consider in minimizing and managing injection-induced seismicity potentially associated with new or existing Class II disposal wells. The decision model is specifically designed for Class II disposal wells. However, the UIC Director should also consider other causative factors, such as lake level changes or different types of area operations (mining, production activities, etc.). As mentioned previously, the three key components behind injection-induced seismicity are (1) sufficient pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway allowing the increased pressure to communicate from the disposal well to the fault. All three components must be present to induce seismicity. The decision model was designed to identify the presence of any of the three key components. Based on the historical successful implementation of the UIC program, the decision model would not be applicable to the vast majority of existing Class II disposal wells since most are not associated with seismic activity. Use of the decision model is predicated on UIC Director discretionary authority. Federal UIC regulations do not specifically address risk consequences associated with seismicity, but allow the UIC Director discretion to ensure protection of USDWs.

The decision model incorporates a site assessment consideration process addressing reservoir and geologic characteristics related to the three key components. The decision model provides the UIC Director with specific site assessment considerations and approaches to identify and address seismicity criteria for both existing and new disposal wells. No single question addresses all the considerations needed to evaluate a new or existing disposal well. If issues are identified,

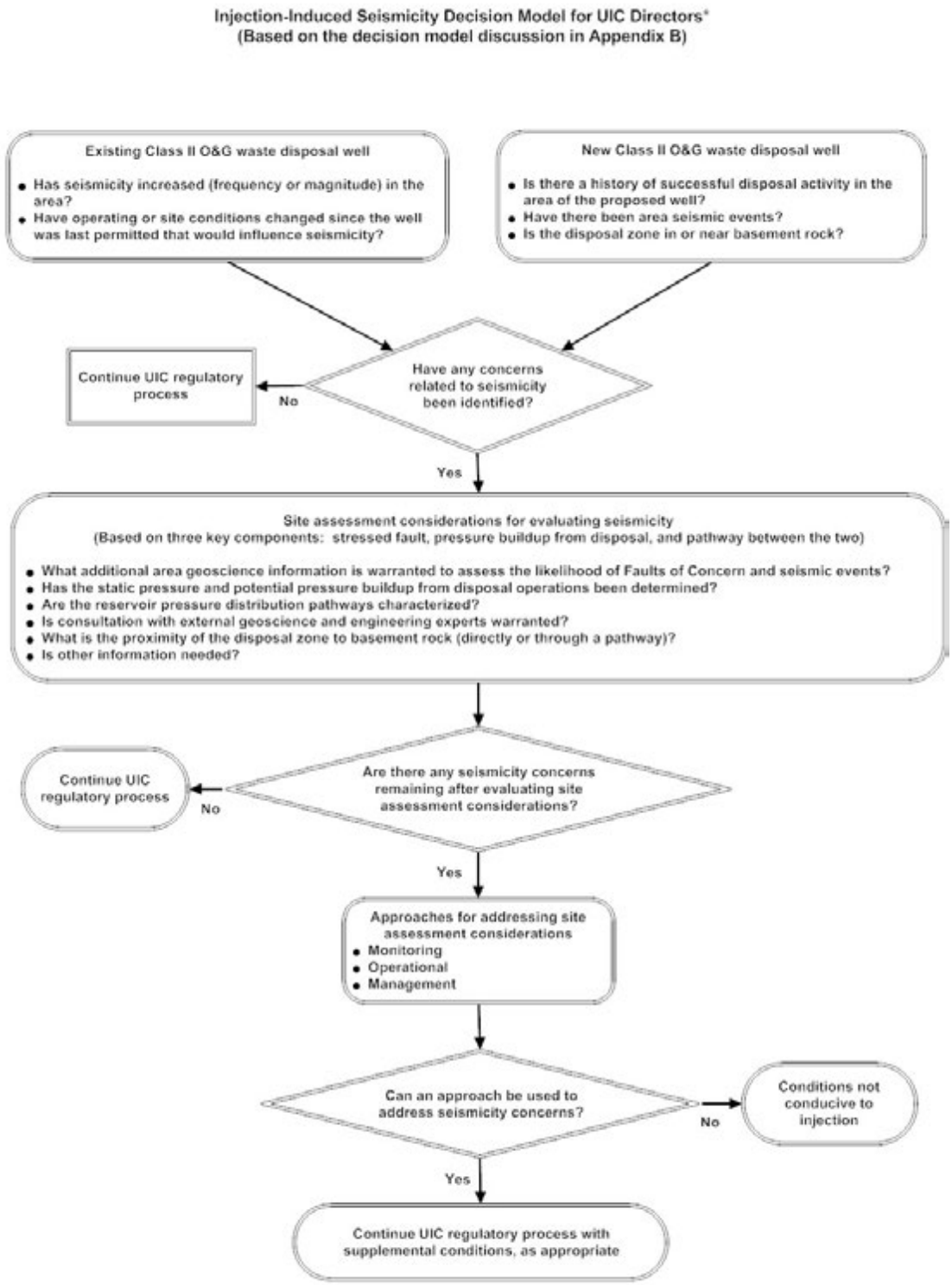
the decision model provides specific operational, monitoring and management approaches as options for addressing the issues.

The diagram of the decision model, Figure 1, is followed by a discussion of considerations for site assessment. The "area" referenced in the decision model is a geographic area with the extent determined by the Director using expertise about the site circumstances. Issues identified through the site assessment consideration thought process are then addressed, as needed, by a combination of operational, monitoring and management approaches. These options were identified by the WG from petroleum engineering methods, literature reviews, analyses of the case studies, and consultations with researchers, operators and state regulators. A more detailed discussion of the decision model is included in APPENDIX B: .

The decision model (Figure 1) contains three symbols that represent the following:

- Bubble – thought process
- Diamond – decision point
- Rectangle – outcome

FIGURE 1: INJECTION-INDUCED SEISMICITY DECISION MODEL



* Decision model is founded on Director discretionary authority

Existing or New Class II Disposal Well

The decision model was designed to address seismicity concerns related to new or existing disposal wells. Below are the different scenarios. Different site assessment considerations may be applicable to each scenario.

1. An existing disposal well operating in a zone with historical injection
2. An existing disposal well in an area not experiencing seismicity, where the operator requests a substantial increase to injection volumes or pressure
3. A new disposal well in a disposal zone or area where little or no disposal activity has previously occurred, with or without seismic activity

Scenario (1) may not warrant further site assessment based on successful historical operations, while scenarios (2) or (3) may warrant additional site characterization consideration, especially if the well is located in a region with possible Faults of Concern.

Have Any Concerns Related to Seismicity Been Identified?

An UIC Director who does not identify any injection-induced seismicity concerns may exit the decision model and continue through the normal UIC regulatory process; otherwise, a continuation through the model for further site assessment considerations may be warranted.

Site Assessment Considerations

Site assessment considerations identify and help the UIC Director evaluate any specific site characteristics that raise potential issues regarding injection-induced seismicity. Uncertainties about any one of the three key components may warrant collection or review of additional data within the site assessment consideration process.

Site assessment considerations may pertain to information from permit applications or post-approval permit monitoring data. Site assessment considerations may include aspects of both geosciences and petroleum engineering, so a multidisciplinary approach is advantageous. Details about the decision model diagram and its associated site assessment considerations are provided in APPENDIX B: .

Site assessment considerations determined to be relevant for the decision model were the following:

- What additional area geoscience information is warranted to assess the likelihood of Faults of Concern and seismic events?
- Has the static pressure and potential pressure buildup from disposal operations been determined?

- Are the reservoir pressure distribution pathways characterized?
- Is consultation with external geoscience and engineering experts warranted?
- What is the proximity of the disposal zone to basement rock (directly or through a pathway)?
- Is other information needed?

Are There Any Seismicity Concerns Remaining After Site Assessment?

An UIC Director who does not identify any injection-induced seismicity concerns following a more detailed site assessment may exit the decision model and continue through the normal UIC regulatory process. When an injection-induced seismicity concern is identified, the Director may determine an approach to address the concern. The site assessment considerations are intended to guide the Director in selecting operational, monitoring and management approaches that are appropriate for addressing induced seismicity issues.

Approaches for Addressing Site Assessment Issues

There are a number of approaches available to manage and minimize significant seismic events. These can be broadly categorized as operational, monitoring and management approaches. An operational approach may include, for example, restricting the maximum allowable injection rate or pressure. A monitoring approach may necessitate collection of additional monitoring data, for example, operational pressures, additional seismic monitoring or pressure transient well testing. A management approach supports a proactive approach for prompt action following seismic events and promotes agency, operator and public interaction. The UIC Director determines which, if any, approaches are important, depending on site-specific considerations. Details about the approaches for addressing issues associated with the site assessment considerations are provided in APPENDIX B: .

Can an Approach be Used to Successfully Address Seismicity Concerns?

Where the UIC Director does not identify a suitable approach for addressing seismicity concerns, conditions may not be suitable for disposal operations at that location. If monitoring, operational or management approaches provide the required level of protection, the Director may condition the permit accordingly or use discretionary authority to require the desired approaches without revoking the permit.

Research Needs

The WG did not exhaust all avenues with respect to research on the value of petroleum engineering approaches. An abundance of research describing seismology and geomechanical behavior in the form of physical rock properties exists, although studies that combined

petroleum engineering and geoscience approaches could not be found by the WG. The WG recommends future practical research using a multidisciplinary approach and a holistic assessment addressing disposal well and reservoir behavior, geology and area seismicity. Such an approach would benefit from combined expertise in geology, petroleum engineering, geophysics and seismology, which may not be available through one entity. For example, areas of expertise should include, but may not be limited to structural and stratigraphic geology; rock mechanics (aka geomechanics); seismology; reservoir characterization; reservoir fluid flow mechanisms; and disposal well construction, completion and performance.

The WG employed Hall plots for the petroleum engineering analysis because regulators may perform these analyses using widely available spreadsheet software and routinely obtained program data. However, other petroleum engineering evaluations are also available that may be applicable, if converted to incorporate injection conditions. The WG identified correspondence between injection well operational characteristics and seismic events in some of the case study wells using Hall plots. Future research is needed to explore other simple engineering techniques that could be used to analyze potential correlations between disposal well operational long-term hydraulic behavior and earthquake events. One of the key outcomes of such a research project would be a practical set of methodologies to assess operating data using injection well permit reporting data normally acquired for existing UIC permits.

To clarify the meaning of the injectivity patterns observed in the case study wells, a comparison of typical injectivity responses for disposal wells in different fractured and unfractured formations would be invaluable. There are a host of variations on this theme, where additional information is needed in order to identify whether a response is associated with a single cause or stems from multiple sources. This information includes such things as formation character, offset disposal well interaction, proximity to a fault, and fracture initiation. A correlative study analyzing whether or not microseismicity accompanies the disposal would help to clarify the risk aspect. Where seismic responses appear, understanding the timing of disposal operations and the apparent response would be an important addition to the UIC knowledge base.

There is also a need for research related to geologic siting criteria for disposal zones in areas with limited or no existing data. The geologic and geophysical study could focus on new stratigraphic horizons that could serve as disposal zones in these areas, the nature of subsurface stresses in basement rocks of these areas, and a more detailed regional geological assessment of basement faults. If sufficient earthquake catalog data are available, additional research to devise a statistical analysis to relate Class II disposal wells operating parameters to induced seismicity would be useful.

Recommendations for Minimizing or Managing Injection-Induced Seismicity

The WG found that no single recommendation addresses all the complexities related to managing or minimizing injection-induced seismicity. Recommendations included in this report were derived from a combination of WG expertise, case studies, consultations with outside experts and data from literature reviews. Recommendations from the outcome of the decision model can be divided into three technical categories (site assessment considerations, operational and monitoring) and a management component. An early step in the induced seismicity evaluation process is to conduct a preliminary assessment. Based on the preliminary assessment and additional site assessment considerations, further operational, monitoring and management approaches may be warranted. The complete discussion of the decision model is located in APPENDIX B: .

Preliminary Assessment of Existing or New Oil and Gas Waste Disposal Wells

- Assess disposal history for correlation with area seismicity.
- Review area seismicity for increases in frequency or magnitude.
- Identify changes in disposal well operating conditions that may influence seismicity.
- Determine the depth to basement rock and potential connectivity to the disposal zone.

Site Assessment Considerations

Site assessment considerations were developed to identify and evaluate specific site characteristics that may represent potential issues for injection-induced seismicity. Many geologic and petroleum engineering considerations for site characterization are not part of the typical permit application process. Additional data collection or review of additional data may be warranted. Possible site assessment activities are shown below:

- Evaluate regional and local area geoscience information to assess the likelihood of activating faults and causing seismic events.
- Assess the initial static pressure and potential pressure buildup in the reservoir.
- Review the available data to characterize reservoir pathways that could allow pressure communication from disposal activities to a Fault of Concern.
- Consult with external geoscience or engineering experts as needed to acquire or evaluate additional site information.
- Determine the proximity of the disposal zone to basement rock.
- Consider collecting additional site assessment information in areas with no previous disposal activity and limited geoscience data or reservoir characterization, prior to authorizing disposal.

APPROACHES

Possible operational, monitoring and management approaches follow to address seismicity concerns that may arise from the site assessment evaluation. Several proactive practices were identified for managing or minimizing injection-induced seismicity. The applicability and use of any of these approaches should be determined by the Director.

OPERATIONAL APPROACH

- Conduct a petroleum engineering analysis of operational data on wells in areas where seismicity has occurred, to identify potential correlation.
- Conduct pressure transient testing in disposal wells suspected of causing seismic events to obtain information about injection zone characteristics near the well.
- Perform periodic static bottomhole pressure monitoring to assess current reservoir pressures.
- Modify injection well permit operational parameters as needed to minimize or manage seismicity issues. This may require trial and error. Examples of modifications may include the following:
    - Reduce injection rates, starting at lower rates and increasing gradually.
    - Inject intermittently to allow time for pressure dissipation, with the amount of shut-in time needed being site-specific.
    - Separate multiple injection wells by a larger distance for pressure distribution since pressure buildup effects in the subsurface are additive.
    - Implement contingency measures in the event seismicity occurs over a specified level.
- Operate wells below fracture pressure to maintain the integrity of the disposal zone and confining layers.
- Perform annular pressure tests and production logging if mechanical integrity is a concern.

MONITORING APPROACH

- Increase frequency of monitoring for injection parameters, such as formation pressure and rates, to increase the accuracy of analysis.
- Monitor static reservoir pressure to evaluate pressure buildup in the formation over time.
- Install seismic monitoring instruments in areas of concern to allow more accurate location determination and increased sensitivity for seismic event magnitude.
- Increase monitoring of fluid specific gravities in commercial disposal wells with disposal fluids of variable density since the density impacts the bottomhole pressure in the well.

MANAGEMENT APPROACH

- For wells suspected of induced seismicity, take early actions, such as acquiring more frequent reports of injection volumes and pressures, reducing injection rates, and/or increasing seismic monitoring, rather than waiting on definitive proof of the causal relationship. Engage the operators early in the process, especially in areas that are determined to be vulnerable to injection-induced seismicity.
- Engage external multidisciplinary experts from other agencies or institutions. For example, Directors may utilize geophysicists to interpret or refine data from seismic events for accuracy and stress direction.
- Provide training for UIC Directors on new reservoir operational analysis techniques to help them understand the spreadsheet parameters.
- Employ a multidisciplinary team for future research to address possible links between disposal well and reservoir behavior, geology and area seismicity.
- Include a seismic threshold as a condition of the permit describing action to be taken in the event of initiation of or increase in seismic events. Thresholds could be based on the magnitude or frequency of events.
- Develop public outreach programs to explain the complexities of injection-induced seismicity.

REPORT/END PRODUCT TASK RESULTS

EPA requested that the NTW output include a specific list of elements in the final report (APPENDIX A:). This list is repeated below, with the corresponding section of this report summarizing the results listed immediately below the item. (Report locations are italicized.)

1. **Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations**
   A point-by-point comparison is not possible as program requirements are widely variable across the various EPA regions and state agencies. The most commonly requested disposal permit parameters found to be useful in addressing potentially induced seismicity include accurate reporting[20] for the following:
   a. All available disposal formation data with respect to flow characteristics and continuity; i.e., static pressure, permeability, normal flow pattern (homogenous or linear) and potential disruptions to flow path (stratigraphic or structural)

[20] Many of these parameters may be requested, but not required.

b. Annual reports of injection volumes and pressures (average and maximum); monthly is more useful than quarterly; daily is needed for more refined analysis

2. **Decision-making model—conceptual flow chart**

   Figure 1 under *Decision Model: Site Assessment Considerations* and at the end of *APPENDIX B*

   a. Provide strategies for preventing or addressing significant induced seismicity. (Note that prevention of earthquakes may not be possible where faults are critically stressed.)
      i. *Recommendations for Minimizing or Managing Injection-Induced Seismicity*; and first subheading
      ii. *APPENDIX B: Introduction*
   b. Identify readily available applicable databases or other information.
      i. *APPENDIX L: and APPENDIX M:*
   c. Develop site characterization check list
      i. *Recommendations for Minimizing or Managing Injection-Induced Seismicity: Site Assessment Considerations*
      ii. *APPENDIX B: Site Assessment Considerations for Evaluating Seismicity*
   d. Explore applicability of pressure transient testing and/or pressure monitoring techniques
      i. *Case Study Results*
      ii. *APPENDIX D - APPENDIX H*

3. **Summary of lessons learned from case studies**
      i. *Case Study Results: Common Characteristics, Observations, and Lessons Learned From Case Studies*

4. **Recommended measurement or monitoring techniques for higher risk areas**
   a. Approaches to address site assessment consideration
      i. *APPENDIX B: and APPENDIX D:*

5. **Applicability of conclusions to other well classes**

   Induced seismicity with respect to other well classes was discussed in the Introduction. The conclusions for the Class II disposal program may be applicable to other well classes; however, additional considerations may also be needed particularly for geothermal wells.
      i. *APPENDIX K: Subject Bibliography: Geothermal*

6. **Define if specific areas of research are needed**
      i. *Research Needs*

REPORT FINDINGS

The following major report findings are derived from the literature reviews, case study reviews, and the development of the decision model:

- The three key components behind injection-induced seismicity are (1) sufficient pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway for the increased pressure to communicate from the disposal well to the fault. Successful disposal occurs in areas with one or two characteristics present, but not all three.
- The UIC Director should take early prudent action to minimize the potential for injection-induced seismicity rather than requiring substantial proof of the causal relationship.
- The WG applied petroleum engineering techniques not identified in the injection-induced seismicity literature. These techniques have useful application for assessing flow path and fault presence. Basic petroleum engineering practices coupled with geology and geophysical information may provide a better assessment of well operational behavior in addition to improved understanding of reservoir and fault characteristics.
- A multidisciplinary approach is important for the evaluation of the key three components. Understanding the geologic characteristics and reservoir flow behavior of a site involves methodologies from petroleum engineering, geology and geophysics disciplines.
- The case studies were useful for identifying common characteristics of suspect wells and actions UIC Directors took through discretionary authority to manage and minimize seismic events in these areas.
- Additional research is needed to explore correlations between disposal well operational behavior and nearby earthquake events, taking into consideration all possible causal effects.
- Future research should consider a practical multidisciplinary approach and a holistic assessment addressing disposal well and reservoir behavior, geology and area seismicity.
- The decision model developed through this effort is based on a thought process derived from a combination of case studies, literature reviews and understanding the conditions essential to cause seismicity. The WG selected a thought process versus a definitive framework to provide the Director with flexibility. The key questions of the decision model are:
    - Have any seismicity concerns been identified in new or existing wells?
    - Are there site considerations remaining following further review of data?
    - Can a monitoring, operational or management approach be used to successfully address seismicity concerns?

Greater detail regarding these findings can be found in the respective report sections and associated appendices.

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Glossary of Acronyms and Terms

Acronyms

AAPG	American Association of Petroleum Geologists
AGS	Arkansas Geological Survey
ANSS	USGS Advanced National Seismic System
AOGC	Arkansas Oil and Gas Commission
BHP	Bottomhole Pressure
CERI	Center for Earthquake Research and Information
ComCat	Comprehensive catalog
DFW	Dallas-Fort Worth
EPA	U.S. Environmental Protection Agency
HF	Hydraulic Fracturing
IEA	International Energy Agency
M4.0	Magnitude earthquake event; for instance, M4.0 means magnitude 4.0
NCEER	Central and Eastern United States, CERI Earthquake database
NEIC	National Earthquake Information Center, U.S. Geological Survey
NTW	National Technical Workgroup
ODNR	Ohio Department of Natural Resources
OSN	Ohio Seismic Network
PDE	Preliminary Determination Earthquake, NEIC Earthquake database
RRC	Railroad Commission of Texas
SMU	Southern Methodist University
SPE	Society of Petroleum Engineers
SRA	Eastern, Central & Mountain States NEIC Earthquake database
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USGS	U.S. Geological Survey
USHIS	Significant U.S. quakes, NEIC Earthquake database
WG	Injection-induced Seismicity Working Group
WVDEP	West Virginia Department of Environmental Protection Office of Oil and Gas

TERMS

Catalog aka earthquake catalog from USGS online Earthquake Search of the NEIC PDE catalog of earthquakes. http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

Class II injection wells are wells that inject fluids (1) which are brought to the surface in connection with conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection, (2) for enhanced recovery of oil or natural gas; and (3) for storage of hydrocarbons which are liquid at standard temperature and pressure (40 CFR 146.5(b)).

Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS). Earthquakes resulting from human activities will be called induced earthquakes in this report.

Epicenter is the point on the earth's surface vertically above the hypocenter (or focus) point in the crust where a seismic rupture begins. NEIC coordinates are given in the WGS84 reference frame. The position uncertainty of the hypocenter location varies from about 100 m horizontally and 300 m vertically for the best located events, those in the middle of densely spaced seismograph networks, to tens of kilometers for events in large parts of the United States.

Falloff test is a pressure transient test conducted by shutting an injection well in and observing the pressure decline at the well over a period of time.

Fault of Concern is a fault optimally oriented for movement and located in a critically stressed region. The fault is also of sufficient size, and possesses sufficient accumulated stress/strain, such that fault slip and movement has the potential to cause a significant earthquake. Fault may refer to a single fault or a zone of multiple faults and fractures. See also Geologic Stress Considerations; APPENDIX B: Site Assessment Considerations For Evaluating Seismicity; and APPENDIX M: State of Stress for more complete discussion.

Hypocenter, aka focus, is the 3-D location of the earthquake source, i.e., latitude, longitude, focal depth below ground.

Isopach is a contour map illustrating the variations of thickness of a defined stratum.

Magnitude is a number that characterizes the relative size of an earthquake at the hypocenter. Magnitude is based on the measurement of the maximum motion recorded by a seismograph or the energy released. Generally, damage is reported for magnitudes

above 5.[21] Magnitude (M) will refer to the numbers reported by USGS or the NEIC, not separated between moment, body wave, or surface wave magnitudes.

Magnitude[22]	Earthquake Effects
2.5 or less	Usually not felt, but can be recorded by seismograph.
2.5 to 5.4	Often felt, but only causes minor damage.
5.5 to 6.0	Slight damage to buildings and other structures.
6.1 to 6.9	May cause a lot of damage in very populated areas.
7.0 to 7.9	Major earthquake. Serious damage.
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.

Microseismicity has no formal definition, but generally is an earthquake with a magnitude less than 2. (*The Severity of an Earthquake*, USGS website: http://earthquake.usgs.gov/learn/topics/richter.php)

Step rate test is a pressure transient test that consists of a series of increasing injection rates as a series of rate steps and estimates the pressure necessary to fracture the formation.

Significant earthquakes/seismic events, for this report, are of a magnitude that can cause damage or potentially endanger underground sources of drinking water.

Static pressure, for this report, is the bottomhole pressure in the pore volume around the injection well measured in the wellbore at the end of a shut-in period that reaches stabilized conditions.

Tectonic is the rock structure and external forms resulting from the deformation of the earth's crust. (Dictionary of Geological Terms, 1976).

[21] Building damage was reported following 2011 earthquakes near Trinidad, Colorado (5.3); near Greenbrier, Arkansas (4.7); and the Soultz, France, project (2.9).

[22] Michigan Tech, <http://www.geo.mtu.edu/UPSeis/magnitude.html>, Accessed 11/10/14.

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APPENDIX A: UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC #2011-3

UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC: #2011- 3

Technical Recommendations to Address the Risk of Class II Disposal Induced Seismicity

Background

Recent reports of injection-induced seismicity have served as a reminder that the UIC Program can and should implement requirements to protect against significant seismic events that could ultimately result in USDW contamination. The UIC Program's Class I hazardous and Class VI siting provisions require rigorous evaluations for seismicity risks. The other well classes, in contrast, allow the UIC Director the flexibility to decide if and when such evaluations are needed. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to inform and enhance strategies for avoiding significant seismicity events related to Class II disposal wells.

Project Objectives

The UIC NTW will analyze existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

1. What parameters are most relevant to screen for injection induced seismicity? Which siting, operating, or other technical parameters are collected under current regulations? (Geologic siting criteria, locations and depths of area pressure sources and sinks, injection rates and pressures, cumulative injection or withdrawals of an area, evaluation of fracture pressure, stresses or Poisson's ratio, etc.)
2. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection induced seismic activity? What other information would be useful for enhancing a decision making model? (Flow chart incorporating seismicity/hazard database resources, reservoir testing methods, area faulting, measuring or recording devices, reservoir pressure transient models, seismic models, other screening tools, etc)
3. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection induced seismicity?
4. What lessons have been learned from evaluating case histories?
    a. Did reviews of injection rate and pressure data sets reveal any concerns?
    b. Were any pressure transient tests conducted?
    c. How were the seismicity events attributed to Class II disposal activities?
    d. What levels of site characterization information were available?
    e. Which UIC regulations have regulators used to address the situation?
    f. Were there areas of concern identified that existing UIC regulations did not address?
    g. Any other lessons learned?

Output

The end-product of this analysis should be a report containing technical recommendations for avoiding significant levels of injection induced seismicity that EPA can share with UIC Directors. The UIC NTW will produce a report that includes the following elements:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Prepare a decision making model – conceptual flow chart
    a. Provide strategies for preventing or addressing significant induced seismicity
    b. Identify readily available applicable databases or other information
    c. Develop site characterization check list
    d. Explore applicability of pressure transient testing and/or pressure monitoring techniques
3. Summary of lessons learned from case studies
4. Recommended measurement or monitoring techniques for higher risk areas
5. Applicability of conclusions to other well classes
6. Define if specific areas of research are needed

Milestones

- July 2011 – Authorization from UIC managers for UIC NTW to proceed with injection induced seismic project proposal. Assemble UIC NTW project team and assign tasks to project members. Collect and distribute, to UIC NTW project team, information from published studies, peer-reviewed articles, and State and Federal UIC programs.
- August 2011 – Create project sub-teams. Collect and evaluate information from case histories. Review compilation of information and develop technical recommendations for addressing risks of significant injection induced seismicity. Create project teams.
- September 2011 - Consolidate input from project sub-teams
- October 2011 – Prepare and present preliminary technical recommendations and report to UIC NTW membership. Finalize technical recommendations and report with input from UIC NTW membership.
- November 2011 – Submit report for presentation to UIC management
- December 2011 – Finalize report and post to public accessible UIC NTW website

Project Focus Group

Phil Dellinger (R6; Lead); Leslie Cronkhite (HQ; HQ-Lead); Jill Dean (HQ); Bob Smith (HQ); David Albright (R9); Sarah Roberts (R8); Tom Tomastik (Ohio Department of Natural Resources); Steve Platt (R3); Dave Rectenwald (R3), Susie McKenzie (R6), Brian Graves (R6), Ken Johnson (R6), Nancy Dorsey (R6), state representatives associated with case histories.

Target Delivery Date: December 2011

Headquarters Approval

Ann Codrington, Acting Director
Drinking Water Protection Division
Office of Ground Water and Drinking Water

7/20/11
Date

SPECIFIC GUIDANCE TO WORKGROUP: (space unlimited)

APPENDIX B: DECISION MODEL

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INTRODUCTION

A key objective of this project was to develop a practical tool for Underground Injection Control (UIC) regulators to use in the evaluation of potential injection-induced seismicity or to manage and minimize suspected injection-induced seismicity. As a result, a decision model was developed for UIC regulators to consider based on site-specific data from the Class II disposal well area in question. The decision model was designed in consideration of the three key components necessary for inducing seismicity, (1) sufficient pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway allowing the increased pressure to communicate from the disposal well to the Fault of Concern. Options for additional actions are included in this model.

The absence of recorded historical seismic events in the vicinity of a proposed Class II injection well does not mean there were not historic low-level seismic events. It is possible that low-level events occurred but were not detected by the historic seismic monitoring network. With the increased deployment of modern and more accurate portable seismic units or seismic arrays, many previously undetected low-level seismic events are now being documented in some areas of the United States. The increased deployment of these seismic instruments further enhances the ability to detect low-level seismic events, whether naturally occurring or induced. Nevertheless, the occurrence of measurable seismicity after the initiation of disposal in areas with little or no historic seismicity supports the possibility of induced seismicity.

Class II disposal activities have existed for decades without inducing significant seismicity. This decision model may not be applicable to areas with historically demonstrated successful disposal activities. Because of complex variations in geology and reservoir characteristics across the country, it is neither practical nor appropriate to provide a detailed step-by-step decision model. Instead, UIC Director discretionary authority will determine the applicability of this decision model to Class II disposal well activities and the need to address site-specific conditions. The model presented in this report summarizes the various considerations and approaches identified by the Injection-Induced Seismicity Working Group (WG) through petroleum engineering methods; geosciences considerations; literature review; analysis of the case studies; consultations with researchers, operators and state regulators; and feedback from subject matter experts. The decision model is included as Figure B-1 at the end of this appendix.

Areas for Review

Throughout the decision model discussion and Figure B-1, the "area" referenced is a geographic area with an extent determined by the Director based on usage, whether as a screening tool or a focused site-specific evaluation tool. The geographic area can also vary based on geologic setting and the available seismic monitoring network. Therefore, defining the term "area" with a specific areal extent was not practical for this report.

Options for a screening seismicity review include looking at the overall seismicity history of a broad area, statewide or by geologic province. A simple method is to use both a statewide historical seismicity map prepared by the U.S. Geological Survey (USGS) or another seismicity reporting service, and the Quaternary Fold and Fault Map created by a USGS consortium. APPENDIX M: Task 1 contains links and a more detailed discussion of these maps. This screening area could then be further subdivided by the level of seismic activity or quiescence.

In seismically active areas, the focused area of interest may center on the disposal well and related geologic structures of interest. For example, a more detailed, localized review may be recommended by the Director to further evaluate the potential for local geologic structures to

affect the injection well operations. In determining the size of the focused search area, the Director should consider geology and the density of seismometers, which impacts the accuracy of the recorded seismic events in both the lateral and vertical directions. Generally, because of reduced seismometer spacing, accuracy of hypocenter locations outside of active seismic zones is on average 6 miles (10 km), as discussed in APPENDIX M: Task 1. Vertical accuracy varies significantly depending on seismic processing assumptions and seismometer density, but the error range is typically 10,000 to 16,500 feet (3–5 km). The accuracy of seismic events can be further refined by the deployment of portable units around the disposal well.

Quiescent areas are less likely to be of concern for injection-induced seismicity. For seismically active areas, the Director may decide to continue through the decision model process and address potential induced events through other means such as permit contingencies.

Existing versus New Class II Disposal Well

Existing Class II Oil and Gas Waste Disposal Well

Two primary reasons the Director may find the decision model useful for existing wells are (1) increased seismicity or (2) change in operating condition of a well located in areas susceptible to seismic events. On a case-by-case basis, the Director may elect to continue further into the decision model by utilizing site assessment considerations to address potential injection-induced seismicity or to minimize and manage existing induced seismicity. If seismicity concerns arise during operation of the disposal well, the Director may revisit the decision model.

Increased seismicity can be determined by various means, such as media reporting, available seismic databases, or the USGS Earthquake Notification Service, which allows the user to customize notifications by area and magnitude. APPENDIX L: lists available databases. A change in relevant operating or site conditions since the well was last permitted may prompt further review by the Director. Relevant parameters should relate to the key components for inducing seismicity (sufficient pressure buildup, reservoir pathway, and Fault of Concern).

New Class II Oil and Gas Waste Disposal Well

For new disposal well applications, the Director may consider whether there is a history of successful disposal activity in the area of the proposed well. Successful disposal activity consists of years of historical disposal without seismic activity in the same geographic area and disposal zone. New wells located in such an area would not be of concern. However, a new disposal well located in an area with no previous disposal activity in the proposed zone may require additional analysis. Uncertainties in reservoir characterization may exist in new areas with few or no existing wells, possibly justifying the need for additional site characterization information and

analysis. Additionally, the location of the disposal zone relative to basement rock may be a consideration on a site-by-site basis. Again, the Director's knowledge of the area and historic disposal activity may determine the need for further site consideration.

Have Any Concerns Related to Seismicity Been Identified?

If the Director does not identify any injection-induced seismicity concerns, he or she may exit the decision model and continue through the normal UIC regulatory process; otherwise, a continuation through the model for further site assessment considerations may be warranted. For a disposal well suspected of initiating seismic activity, the Director determines the appropriateness of advancing the well further through the decision model. The Director may also determine a level of seismicity relevant for further evaluation.

Site Assessment Considerations for Evaluating Seismicity

Once the Director has identified potential concerns related to injection-induced seismicity, additional site assessment considerations may be justified. With few exceptions, injection-induced seismicity occurs in response to increased pore pressure from injection, transmitted through a pathway, to a fault plane of concern (Nicholson and Wesson, 1992). Therefore, the WG identified site-specific assessment considerations for evaluating significant seismicity. These considerations may not all be applicable and are not listed in any order of importance. The Director determines which considerations may be applicable for an existing or proposed Class II disposal well based on site-specific information. Ultimately, through discretionary authority, the Director may require additional site assessment information or monitoring for the protection of underground sources of drinking water (USDW).

Site assessment considerations focus on identifying whether any of the three key components of injection-induced seismicity are present. The considerations included in the decision model are discussed individually below, along with the positive and negative aspects for each.

What Additional Area Geoscience Information Is Warranted To Assess the Likelihood of Faults and Seismic Events?

With few exceptions, injection-induced earthquakes occur in response to increased pore pressure from injection, transmitted through a pathway to a Fault of Concern. Understanding the area geology through available geoscience information may clarify two of the induced seismicity components: the nature of the pathway transmitting the pore pressure response and the identification of Faults of Concern subject to the pressure response. The lateral continuity and heterogeneity of the disposal zone influence both the pressure buildup from disposal

operations and the distribution pathway. The effectiveness of overlying and underlying confining zones may influence the dispersion of pressure in all directions.

Accurate fault assessment, as part of the overall site characterization, is a critical aspect of managing injection-induced seismicity and includes determining the orientation of faults with respect to the geologic stress field. Subsurface faults exist throughout most of the country, and the presence of a fault itself may not be a concern. If a site is in an area with a history of seismic activity, Faults of Concern are likely present in the region. Consideration should be given to the possibility of deep-seated faulting (basement faulting), as reported with the Rocky Mountain Arsenal (Hsieh and Bredehoeft, 1981) and central Arkansas induced events (Ausbrooks, 2011a, 2011b, 2011c, 2011d; Horton and Ausbrooks, 2011).

There are a number of possible options for determining the presence or absence of faulting around a proposed or existing disposal well, including a review of published literature, state geological agency reports, commercial structure maps or interpretations of seismic survey results.[23] While the latter are the most definitive, they are also the most expensive and time-consuming to acquire, and they may require property access that cannot be readily obtained.

Well operators may have exploration seismic survey results that can enhance fault analysis for the site characterization. For example, active faults in central Arkansas and the Dallas-Fort Worth, Texas area were identified first from seismic activity and then verified on the operator's interpreted 3-D seismic surveys, (Chesapeake Energy, personal communication, meeting September 16, 2011). If seismic surveys are available, a re-analysis may help identify any deep-seated faults and associated fractures and their extent. Some faults, however, such as those that are near-vertical strike-slip, may be missed.

Correlations of geophysical logs or review of geologic cross-sections may indicate missing or faulted out rock sections. If a fault is present, information on the origin, displacement and vertical extent of the fault may be a consideration. Geophysical logs may also identify the rock characteristic of the disposal zone and the reservoir pathways the pressure from disposal operations may encounter. If site-specific geoscience information is limited or insufficient and regional studies indicate faults or subsurface stress in the broader area, additional information may be needed to evaluate the likelihood of inducing seismicity.

Geologic site characterization information on flow characteristics, fracture networks and stress fields may be available from: (1) regional and local geologic studies, or (2) information from

[23] Seismic survey lines are typically proprietary, but may be obtained commercially or viewed by special arrangement. If provided, the data may be submitted as confidential business information.

geophysical logs, core analysis and hydraulic fracturing results. Any published articles discussing the basin, reservoir rock or structural history of the area may indicate if faulting, fracturing or directional flow is present. Various publications provide information on determining optimal orientation of faults with respect to the stress field (Holland, 2013; Howe-Justinic et al., 2013).

Has the Static Pressure and Potential Pressure Buildup from Disposal Operations Been Determined?

Reservoir pressure buildup, one of the three key components of induced seismicity, is influenced by reservoir flow behavior, disposal rate and hydraulic characteristics of the disposal zone. To perform conventional reservoir pressure buildup calculations, knowledge of disposal zone hydraulic characteristics is required. Disposal zone hydraulic characteristics include static reservoir pressure, permeability, effective net thickness, porosity, fluid viscosity and system compressibility. Details about these characteristics are generally determined from some combination of fluid level measurements, pressure transient testing results, logging and completion data and fluid and rock property correlations. The static pressure provides a starting point for determining the pressure buildup during disposal activities. Once these values are obtained, the pressure buildup calculations can then be performed to assess the magnitude of pressure increases throughout the disposal reservoir.

Typically, an infinite-acting homogeneous reservoir with radial flow is assumed for the pressure buildup calculation. In many Class II disposal applications, limited reservoir property measurements are available, and actual pressure buildup calculations are done using assumed or accepted area formation characteristic values. Reservoir falloff tests can provide clarity as to whether the homogeneous reservoir behavior assumption is valid or whether pressure buildup projections should be calculated using a different set of fluid flow behavior assumptions. A static bottomhole pressure measurement, typically obtained at the end of a falloff test, may also provide an assessment of reservoir pressure increase around the injection well, offering insight into the magnitude of pressure buildup to which the area fault may have been subjected.

Naturally fractured disposal formations involving induced seismicity may require more complex pressure buildup prediction methods to account for non-radial reservoir behavior. Several cases of suspected injection-induced earthquakes in the literature appear to be characterized by injection zones located within fractured formations (Belayneh et al., 2007; Healy et al., 1968; Horton and Ausbrooks, 2011).

Is the Reservoir Pressure Distribution Pathway Characterized?

The potential pathway or the ability of the reservoir to transmit pressure to a Fault of Concern is best characterized by a combination of geosciences and petroleum engineering information.

Geologic information can help characterize the nature and continuity of the disposal zone. For example, a geologic isopach map or cross-section may define the lateral continuity of the disposal zone and the area potentially impacted by the pressure response from disposal operations. Evaluation of the confining capability of formations overlying and underlying the disposal zone may indicate the potential for pressure dispersal outside the disposal zone. A type log from the disposal well or area offset well may illustrate whether confining layers are present. Other useful aspects for consideration include the number of formations and thickness of permeable strata included within the disposal zone. Heterogeneities in the receiving formations will impact the pathway for pressure distribution away from the disposal well. This level of detailed information, while useful, is not typically required for Class II disposal well operations and therefore may not be available in all situations.

Review of daily drilling reports and open-hole geophysical logs may suggest characteristics of the disposal zone and overlying confining zones, helping to describe the reservoir pathway. For example, borehole washouts or elongated boreholes observed on a caliper log may suggest a high-stress or fractured zone. Heavier mud weights used while drilling may suggest the presence of higher pressure zones. Core data are not typically acquired during the drilling of Class II disposal wells, but if available, could show natural fractures (open or sealed), karstic rock or fault gouging if present. Open-hole geophysical logs, such as fracture finder logs, multi-arm dipmeters, borehole televiewers or variable-density logs may also assist in identifying fractured zones.

Production logging data in an existing well may supplement geologic data by providing additional insight about out-of-interval fluid movement and vertical pressure dispersal. Production logs such as radioactive tracer surveys, temperature logs, noise logs, flowmeters (e.g., spinner surveys) and oxygen activation logs can show where fluid exits the wellbore and allow estimates of fluid volumes being emplaced into the intervals identified. Wellbore fill at the base of a well may reduce the interval thickness, alter the injection profile, and increase the pressure buildup during disposal operations. For example, wellbore fill may cover a large portion of the disposal zone in a well with a short perforated interval; resulting in a greater pressure buildup within the thinner interval receiving fluid. Production logs can also indicate whether fluid is channeling upward or downward behind the casing to other intervals for potential hydraulic impact and show intervals impacted by cumulative long-term injection.

Petroleum engineering approaches, such as a reservoir falloff test, can also provide clues about the pressure transmission pathway by indicating whether the injection zone is exhibiting linear flow (i.e., it may be fractured) or homogeneous radial flow (i.e., the formation is non-fractured) manner. Falloff testing is not a requirement for Class II wells but has been used as a lower cost alternative in some Class II operations to characterize the disposal reservoir flow parameters,

reservoir pressure buildup and well completion condition. Falloff testing is associated with the petroleum engineering approach discussed in further detail in APPENDIX D: .

Is Consultation with External Geoscience and Engineering Experts Warranted?

Site assessment considerations may require multidisciplinary evaluations, necessitating consultations with geophysicists, geologists and petroleum engineers. Consulting with seismologists and geophysicists at either state or federal geological surveys can provide additional information and may be necessary under certain site-specific conditions. For example, in the Arkansas case study, UIC regulators coordinated with researchers from the University of Memphis and Arkansas Geological Survey to successfully acquire critical information on ongoing low level seismic activity. Data from this effort formed the basis for a disposal well moratorium in the area of disposal-induced seismicity.

Seismic history for any area in the United States is readily available on the USGS website (see APPENDIX L:) and/or state geological agencies websites at no cost. Where seismometers have recorded sufficient quality and quantity of data, seismologists may be able to refine the actual event location and depth data to identify the fault location and principal stress direction.

Geologists can provide insight on reservoir geologic data and identify the presence of faults or potential for faulting. Reservoir analysis by petroleum engineers may evaluate the completion condition of the disposal well, provide estimates of pressure buildup and characterize pressure distribution away from the disposal well. Other expertise may be available through academia, consultants or other agencies.

What is the Proximity of the Disposal Zone to Basement Rock?

Most of the literature and case examples regarding alleged disposal-induced seismicity suggest that the seismicity is related to faults in basement rocks. Therefore, depth from the disposal zone to the basement rock or the existence of a flow pathway from the disposal zone to the basement rock may be a consideration. A comprehensive study of disposal in basement rock was not part of this study. Cases of successful disposal in basement rock may exist. A lower confining layer between the disposal zone and basement rock may restrict pressure communication with underlying faults, thereby minimizing the conditions for induced seismicity.

Is Other Information Needed?

Based on review of the available site characterization information, the Director may require additional information to respond to unique site-specific circumstances.

Are There Any Seismicity Concerns Remaining After Site Assessment?

If the UIC Director does not identify any injection-induced seismicity concerns following a more detailed site assessment, the well evaluation exits the decision model and continues through the normal UIC regulatory process. When an injection-induced seismicity concern is identified, the Director may determine an appropriate approach to address the concern.

Approaches to Address Site Assessment Considerations

The WG identified operational, monitoring and management approaches to address any significant seismicity concerns identified after evaluating site assessment considerations. Some of the approaches could overlap in classification.

Selection of the appropriate approaches depends on a number of factors. Key factors for addressing site assessment concerns, such as knowledge of the area and timing of seismic events relative to disposal activities. Characterizing the flow behavior in the injection zone, quantifying reservoir conditions and delineating fault characteristics are best accomplished using a multidisciplinary team. The Director may elect to set up contingency measures in the event seismicity occurs or increases.

Operational Approaches

Operational approaches short of shutting in the well may be applicable, though some may involve modification to permit conditions or additional reservoir testing. Some of these approaches are discussed in the following paragraphs.

Reducing injection rates or implementing intermittent injection may decrease reservoir pressure buildup and allow time for pressure dissipation. Determining the reduction in pressure buildup needed to manage or minimize seismicity may require trial and error. The resulting maximum allowable disposal rate or amount of shut-in time needed to remain below a determined reservoir pressure is site-specific. There would be no direct cost to implement, though the reduced disposal volume could impact facility operations and wastewater management.

Confirming site-specific fracture pressure through testing defines a limiting operating pressure value. Operating below the fracture pressure maintains the integrity of the disposal zone and confining layers. Operating a well above fracture pressure could create new pathways by initiating or extending a fracture. Determining the site-specific fracture pressure may require actual testing, such as a step rate test, to measure the actual formation parting pressure in lieu of a calculated fracture gradient. Additional cost would be associated with conducting a step rate test.

Conducting pressure transient tests in disposal wells suspected of causing seismic events may reveal the injection zone characteristics near the well, flow regimes that control the distribution of reservoir pressure, and completion condition of the well. A series of pressure transient tests may provide an indication that the reservoir characteristics and pathway remain consistent throughout the life of the well. Pressure transient testing would require some additional cost to the operator as well as specialized expertise to design and review the data.

Running production logs, such as a flowmeter (spinner survey), radioactive tracer survey or temperature log, to determine where fluids are exiting the wellbore is another useful testing technique for evaluating fluid emplacement. The thickness of the interval receiving fluid can impact the pressure buildup in the reservoir. The location of fluid emplacement could provide insight on the reservoir pathway. Additional costs would be incurred by the operator to run the logs.

Verifying mechanical integrity following a seismic event may include performing tests to evaluate the well and bottomhole cement. Annulus pressure tests can evaluate the integrity of the tubing, packer and production casing. A temperature log, noise log or radioactive tracer survey can confirm the location of fluid emplacement and verify no out-of-zone channeling of fluids.

Petroleum engineering analysis of available operational data (injection rate and pressure) in areas where seismicity has occurred may help characterize the flow behavior, such as enhanced injectivity, in the injection zone. Operational analysis can also quantify reservoir conditions and delineate fault characteristics. Operational analysis uses UIC compliance data so there is no additional cost to acquire data.

Pressure buildup effects in a formation are additive, so separating multiple injection wells by a larger distance may reduce the amount of pressure buildup. Again, the results are site-specific and depend on the quality and size of the disposal zone and number of disposal wells completed in the same formation. Higher costs would likely be associated with drilling multiple wells and transferring wastewater to the additional wells.

Monitoring Approaches

Monitoring approaches focus on reservoir pressure and well condition during disposal operations, along with levels of area seismic activity. In many cases, monitoring approaches can be conducted in conjunction with other approaches.

Requiring more frequent operational data collection to assess site-specific situations relevant to induced seismicity may be useful. The increased monitoring frequency adds improved data quality and quantity for use with operational analysis methods. More accurate data may require

electronic measuring equipment to record and store data, which may add cost. The frequency of data collection can influence the accuracy of the analysis. For example, in the central Arkansas case study, hourly monitoring of injection pressure and volume yielded more data for analysis than the monthly data typically reported.

Monitoring static reservoir pressure provides an indication of the pressure buildup in the formation over time. Depending on the site-specific conditions, static pressure can likely be obtained using a surface or downhole pressure gauge or fluid level measurement. A static reservoir pressure is easy and inexpensive to obtain; however, it requires the well be shut-in for a period of time prior to the measurement.

Monitoring the specific gravity of the wastewater, especially in commercial disposal wells with variable disposal fluid density, allows conversion of surface pressures to bottomhole at no additional cost. The specific gravity impacts the hydrostatic pressure component of the bottomhole pressure calculation.

Monitoring using a pre-existing seismic network may provide an early warning of seismic activity, if the network is suitably configured and continuously evaluated. The monitoring program could use the existing USGS seismic monitoring network or include seismometers proactively installed prior to the injection operation. Tracking earthquake trends (magnitude and event frequency) for events in an area of possible induced seismicity can reveal possible increases in seismicity even before the events become significant. For example, in the Arkansas, Ohio, and West Virginia case studies, an upward trend in the magnitude of associated events is apparent.

Additional seismometers should result in more accurate determinations of seismic event locations, as well as greater sensitivity, allowing detection of smaller events. The USGS recommends configuring a monitoring network capable of detecting events with magnitudes as low as M2.0. In central Arkansas, additional monitoring stations were deployed. The additional monitoring stations provided increased accuracy and resolution, leading to identification of a previously unknown basement fault. Additional seismic monitoring stations and data analysis require additional costs, as well as geophysical expertise to process and review the data.

Management Approaches

A management approach addresses the human aspect of induced seismicity, including agency, operator and public interaction. As discussed below, these approaches provide proactive practices for managing or minimizing injection-induced seismicity.

Undertaking earlier action rather than requiring substantial proof prior to action by the Director to minimize and manage injection-induced seismicity is a prudent approach for a number of

reasons. Early proactive action, such as implementing more stringent operating conditions to decrease pressure buildup, may avoid escalation of event magnitudes and prevent complete shutdown of the well. Early discussions with surrounding operators may allow regulators access to additional data, for example 3-D seismic data, or result in voluntary action. For example, in the north Texas area, communication between the UIC Director and operator resulted in the voluntary shut-in of a suspect disposal well. Early action may also increase public confidence in the regulatory agency.

Contacting external multidisciplinary experts from other agencies or institutions to address site assessment concerns may result in improved quality of response to seismicity concerns. For example, geophysicists may be able to interpret the active fault from the seismic events, along with stress directions, while geologists provide an overall picture of the setting, and engineers evaluate the well responses in conjunction with comments from the others. An initial cooperative effort may have minimal cost.

Providing technical training for UIC regulators specific to petroleum engineering evaluations or geoscience techniques could benefit preparedness of the program and expand options for minimizing and managing seismicity. At a minimum, it would raise awareness of the advantages and disadvantages of the various techniques and disciplines. Some costs may be associated with the training.

Utilizing a multidisciplinary team for practical research of links between disposal well and reservoir behavior, geology and area seismicity allows all complex aspects of seismicity to be reviewed. It may be possible to utilize in-house personnel from other disciplines to aid in the effort.

Establishing a contingency plan, e.g., based on a seismic magnitude and/or frequency threshold, can assure that specific expedited response actions by the injection well operator occur in response to surrounding area seismic events. For example, contingency conditions could be as simple as immediately notifying and working with the permitting agency to evaluate the situation. The use of existing seismic monitoring and reporting databases is inexpensive, but limited data accuracy may require additional expense to supplement the existing network. A contingency plan provides an alternative to approval or denial of a permit.

Developing public outreach programs to explain some of the complexities of injection-induced seismicity may have some value.

Can an Approach Be Used To Successfully Address Seismicity Concerns?

The site assessment considerations are intended to guide the UIC Director in selecting the appropriate operational, monitoring and management approaches to address induced seismicity issues. If the Director does not identify an acceptable approach to address seismicity concerns, conditions may not be suitable to disposal operations at that location. If monitoring, operational or management approaches provide the required level of protection, the Director may condition the permit accordingly or use discretionary authority to require the desired approaches needed without revoking the permit.

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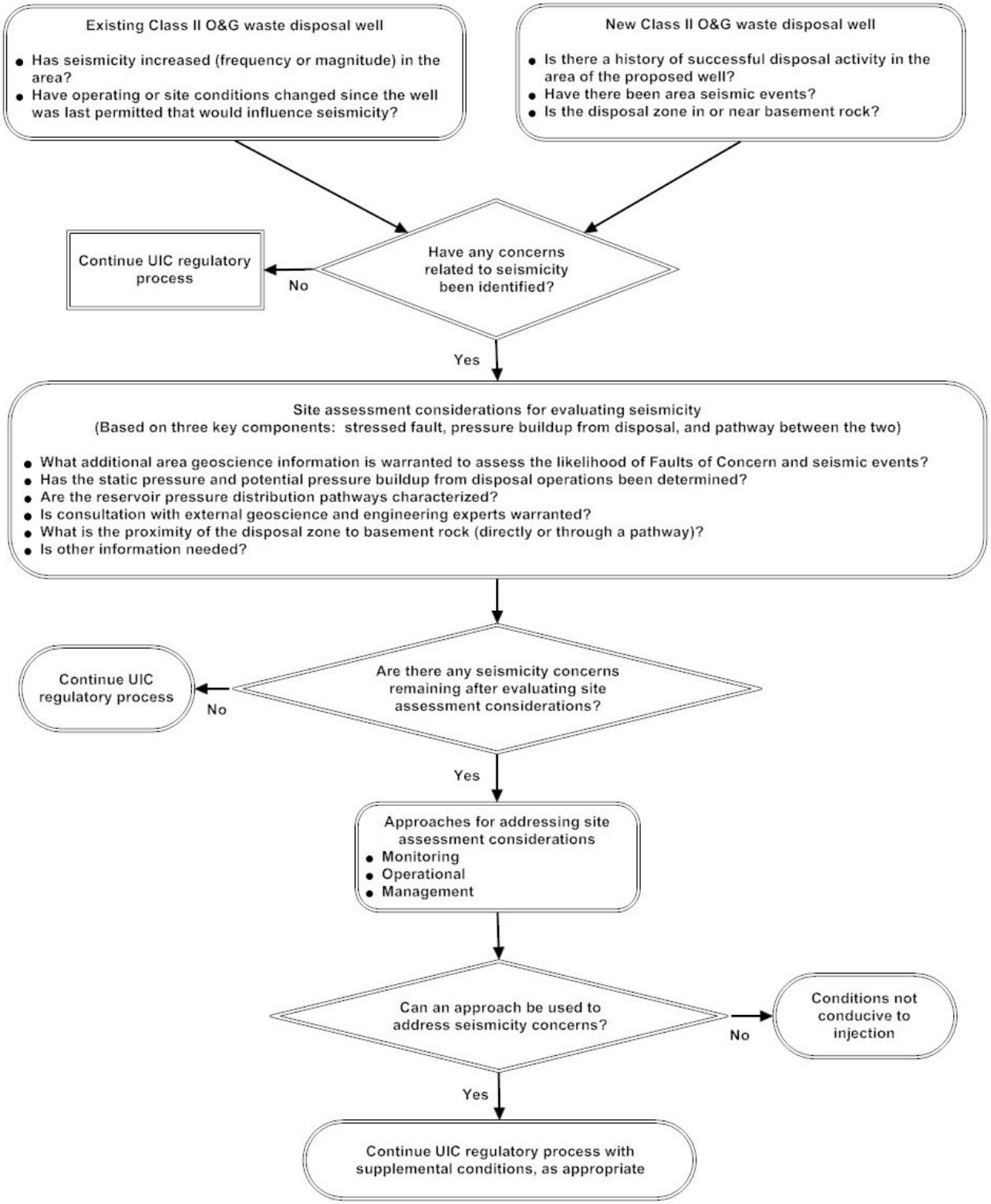
FIGURE B-1: INJECTION-INDUCED SEISMICITY DECISION MODEL FOR UIC DIRECTORS



* Decision model is founded on Director discretionary authority

APPENDIX C: GEOSCIENCES DISCUSSION AND INTRODUCTION TO INDUCED SEISMICITY RISK

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Basic Earth Science Concepts C-1
Basic Geologic Environment C-2
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INTRODUCTION

A basic understanding of the earth science concepts and natural processes through geology, rock mechanics, and seismology, including the science of seismic interpretation, is helpful in assessing the risks of inducing seismic events. A thorough discussion requires a working knowledge of tectonic processes and associated forces (physical stress and resulting strain, which change the shape of the earth's crust) as well as seismology—detailed topics outside the scope of this report. For any in-depth investigation (seismology, structural geology, reservoir characterization, etc.) consulting appropriate professionals is recommended, whether within the permitting agency, a different agency (state or federal), professional society, academia, or private industry. As geologic conditions can vary widely depending on local conditions, no simplified approach to understanding fault movement and seismicity applies everywhere.

Information in this appendix was taken from Stein and Wysession (2003) and Sibson (1994), along with a number of the websites cited at the end of this appendix and in APPENDIX K: Educational Websites on Seismicity.

BASIC EARTH SCIENCE CONCEPTS

The major earth layers are the core (inner and outer), mantle (inner and outer), and crust (oceanic and continental plates). Each layer has distinctly different characteristics and strengths. Oceanic plates are extremely dense and thin compared to the thick continental plates.

Over geologic time, convection currents within the mantle create complex movements beneath the earth's crust. The resulting forces cause sea floor spreading and plate collisions along crustal boundaries. Hot spots associated with volcanic areas extend down into the upper mantle. It is

these processes that result in stressed conditions for crustal rocks below the ground surface and form the basis for the release of this energy along faults that are critically stressed.

Within the earth's crust, three-dimensional reactions to stress occur across every scale, from macro (plates) to micro (individual grains or crystals), with elastic, ductile and brittle response of the affected material, depending on conditions. Examples of brittle deformation in rocks include all types of fracture systems both with (faults) and without (joints) offsetting movement. Faults in brittle formations are accompanied by fracture zones, with the frequency or density of fractures typically decreasing with distance away from the fault. The nature of faulting and associated fracture zones is an important consideration with respect to induced seismicity, since these fracture zones can serve as avenues of communication for pore pressure buildup to the fault. Although stress histories can be inferred in some cases by analysis of fracture patterns (e.g., analysis of joint patterns), areas that have been subjected to multiple tectonic events may have extremely complex and extensive fracture systems.

Basic Geologic Environment

A particular geographic area can be described using approaches from three major geologic disciplines: stratigraphy (the formation, sequence and correlation of layered rock), petrology (rock origin through later alteration), and structure (interpretation of structural features and their causes). Petrology uses three main rock classifications (igneous, metamorphic and sedimentary) defined by rock origin, composition and physical characteristics, among other details.

Stratigraphy primarily relates to geologic depositional processes and their order in time (law of superposition and identification of missing, repeated or overturned strata/sections). In the continental crust, the oldest (typically deepest) rock is called basement or crystalline basement if it is formed through igneous or metamorphic processes. Sedimentary rocks (carbonates, evaporites, and clastics), possibly with igneous intrusions (plutonic and volcanic), typically overlay the basement rocks. The contact between basement rocks and overlying younger strata is almost always an erosional surface (Narr et al., 2006). Basement rocks usually have no effective primary permeability (connectivity of pore space) or porosity (void space), but later weathering or movement can result in fractures or erosional features creating significant secondary porosity. Faulting of basement rocks can also result in fracture porosity and permeability along the fault zone. Basement faults that are active after deposition of overlying material can extend upward into overlying rock. Younger faults may also be present only in overlying sedimentary rocks.

Stratigraphic formations used as disposal zones can have a complex range of porosity types and permeability values. Sedimentary processes include precipitation (chemical and biological) and deposition of eroded rock particles that were transported by water or air and later buried and

compacted into rock. The nature of fracture and matrix (bulk rock) porosities and permeabilities within the disposal zone is a critical aspect of pressure buildup from injection. Natural fractures can provide a permeable avenue for fluid flow, while the matrix is generally less permeable but offers more pore space, potentially limiting the extent of pressure distribution.

Petrology relates to the physical and chemical makeup of the rock, including how it is arranged (size and shape of pieces; void/pore space, cement overgrowths, dissolution, natural fractures, in-fill, etc.). Porosity provides the primary storage capacity of the reservoir, and permeability determines how effectively fluids and pressure are transmitted within the reservoir. Generally, deeper rocks have less permeability and porosity than shallower rocks. Deep basement rocks used for injection are usually either weathered (decomposed or altered), or fractured and faulted from tectonic forces. Wells injecting into, or connected with, fractured basement rock are more likely to induce seismicity.

The distribution and quality of porosity (both primary and secondary) and permeability within the disposal zone are critical for understanding how efficiently the formation will accept additional fluid. The area of increased pore pressure will be smaller in permeable and porous formations that allow fluids to move through the rock easily and quickly dissipate pore pressure, versus formations with restricted fluid movement and low porosity. Vertical and lateral variations in permeability and porosity are common in sedimentary rocks, as are lateral variations in thickness of porous injection zones.

Geologic structure relates to the major physical changes in rock formations caused by three dimensional stresses. For example, earth stresses create fault and fracture zones, igneous intrusions, fold and thrust belts, strike-slip zones and metamorphosed (changed by heat and pressure) rock. These stresses are directly related to the tectonic history of the region.

Geologic Interpretation Tools

Subsurface information on geologic structure can be inferred from surface geology, seismic data and information obtained from artificial penetrations (i.e., wells). Under the Underground Injection Control (UIC) program, developing sufficient geoscientific site data is the responsibility of the permit applicant. However, UIC regulators may elect to review publications or consult with geoscience agencies (state geologic surveys, USGS) or universities with expertise in the geographic area for additional regional geologic information to address the areas of concern. Useful publications may include publicly or commercially available reports containing geologic information (geologic history, stratigraphy or structure) and rock characterization (flow characteristics, fracture networks and stress directions), as well as geophysical well logs, core analysis, mine surveys, seismic surveys and geologic maps and cross-sections.

Geologic maps are designed to characterize the nature and continuity of the formations of interest (regional extent, depositional basin, major structural features, mineral deposits, petroleum reservoirs, etc.). For example, a geologic isopach (layer thickness) map or cross-section may define the lateral continuity of a disposal zone. An analysis of seismic reflection data may help identify any deep faults, and if present, the extent of the fault or associated fractures. Fault identification depends on the quality of available seismic data, though near-vertical strike-slip faults may be missed. Correlations of logs or a review of cross-sections may indicate missing or repeated sections, along with potential faults. Information on the origin, direction and amount of movement, and vertical extent of the fault should be evaluated for any potential impact on the disposal project.

Gravity, magnetic or resistivity surveys or heat flow data may aid in the assessment of the subsurface structures, although these additional techniques may not have the same resolution as the tools discussed earlier. For example, gravity and magnetic surveys are typically conducted on a broad scale.

Rock Mechanics

Earth scientists and engineers have developed various theories to explain observed fault motion/rock failure, with accompanying seismicity.

- The Mohr-Coulomb failure criterion is a fundamental rock mechanics model used to describe fracturing or faulting. The Mohr-Coulomb criterion uses the tectonic stresses on a fault, the frictional resistance of the fault materials, and cohesion within the rock to determine whether or not movement along the fault will occur.
    - Fault movement occurs when shear stress along the fault exceeds the friction on the fault (Sibson, 1994).
    - The Mohr-Coulomb criterion is generally applicable to the uppermost 15 kilometers of the crust (Davis et al., 2011).
- Research is ongoing in a number of areas to define criteria not covered by the Mohr-Coulomb criterion. Examples of a few of these areas include time-dependence, localization, material heterogeneity and fracture propagation, also known as the Griffith criterion (Sibson, 1994; Beeler et al., 2000; Pollard and Fletcher, 2005; Montési and Zuber, 2002).
- More information on deep stress fields and induced earthquake**s**, provided by the U.S. Geological Survey (USGS), is available in APPENDIX M: Task 2.

Fault Motion

When sufficient deformation occurs in the subsurface with the accompanying buildup of in situ stresses, a brittle rock will break, creating fractures. Many materials are elastic or plastic at low levels of stress but break (rupture) when the stress reaches a critical level. When they break, they experience brittle failure. From a geophysical prospective, lithospheric (crustal) rocks are brittle, behaving elastically and plastically until critical stress is reached and failure occurs. Among the various sedimentary rock types within the lithosphere, mature shales, dolomite and limestone are brittle, and immature shale is relatively more ductile (flexible). In a disposal zone, brittle rock is more likely to be subject to induced seismicity.

Unconsolidated sediments are also subject to faulting and overpressure. Areas with high sedimentation rates, such as the Gulf of Mexico, develop growth faults in response to active compaction and gravity load on unstable slopes. The movement on the growth fault is triggered by episodic periods of rapid sedimentation. Conversely, decreased pressure through pumping of ground water could also cause slip along the fault. Both causes effectively remove water from the sediment layer, increasing compaction of sediments, and hence increase the density and weight of the material, triggering slip along the fault. Growth faults are also examples of shallow faulting unrelated to basement rocks.

Reactions to subsurface stress will be accompanied by a level of seismicity that can be recorded with sufficiently sensitive and well-placed monitoring devices. The USGS has compiled a map database of all faults in the United States believed to have caused earthquakes above M6 in the last 1.6 million years (USGS, 2004). The seismology community is actively studying the earth's structure, earthquake occurrence and plate motion in an effort to not only understand but to also forecast earthquakes. To grasp the difficulty of estimating seismicity potential, it is important to understand the basic aspects of seismicity and how earthquakes are measured and interpreted.

Basic Seismology

Earthquakes (seismic events) can occur both during initial rock failure (fault creation) and during subsequent episodes of motion (slip) along an existing fault. The displacement motion generates elastic waves that propagate away from the fault. The movement (propagation) of the seismic wave is governed by laws of refraction and reflection inherent to the geologic properties of the rock. An earthquake (movement within the earth along a fault) gives rise to four types of seismic waves radiating away from the movement source (rupture zone or focus). These movements can be considered in two major wave categories—body waves and surface waves. Body waves travel through the earth, while surface waves travel in a zone along the surface of the earth. Body waves are faster than surface waves and are thus the first seismic waves to arrive at a location.

As waves travel, their amplitude decays with increasing distance. Surface waves decay more slowly with distance than body waves and can cause the most structural (building) damage. Each of the four specific wave types has a characteristic motion (compressive, shear, or elliptical), frequency, wavelength, and velocity of propagation, with a corresponding wave equation. Travel velocities range from less than 1 to over 7 kilometers per second in the crust and upper mantle. For a specific location, there can be three to four arrival times of the different waves in quick succession, whose difference in arrival time can be used to locate the source of the waves.

Large earthquakes are typically followed by smaller ones as stresses redistribute, with the smaller earthquakes producing smaller waves. Crossing wave forms may create constructive or destructive interference. An earthquake series is a set of events related in space and time with similar characteristic wave signatures. In a series of earthquakes, the largest event is the main shock, with the rest classified based on whether they occur before (foreshock) or after (aftershock) the main shock. Detailed analysis of an earthquake series, with sufficiently detailed readings, can be used to map the causative fault location. Observation suggests that aftershocks occur across the fault plane of the main shock as stresses are shifted to new locations. The length of time encompassing the foreshocks and aftershocks is not uniformly defined, but the number of aftershocks decreases significantly over time (Richardson, 2013).

The size of an earthquake can be described quantitatively with different earthquake magnitude scales based on the seismic waves generated: local or Richter (M_L), surface-wave (M_s), body-wave (m_b) or moment magnitude (M_w or M). The first three (M_L, M_s and m_b) use formulas combining amplitude from seismometer recordings with a correction based on the distance the wave has traveled, correcting for the spatial decay of the waves. Additionally, M_s and m_b incorporate the seismic wave period (peak to peak).

Moment magnitude (M_w or M) is proportional to the release of energy from large earthquakes (seismic moment, M_o). M_o is a physical measure of the size of the earthquake that is dependent on the area of the fault, the average displacement on the fault (slip), and shear modulus (rock rigidity). M_w is applicable to all sizes of earthquakes, giving similar results to either M_s or m_b for smaller earthquakes. In large earthquakes (M>5), the energy released is proportional to the amount of slip along the fault plane (Wells and Coppersmith, 1994; Båth, 1966). In preparation of this report, EPA used magnitude values reported in earthquake catalogs (see APPENDIX L:) for the case study evaluations.

The Modified Mercalli Intensity Scale is non-quantitative and is discussed under the Seismic Risk section, since it relates to damage resulting from an earthquake.

SCIENCE OF SEISMIC INTERPRETATION

Technology used to record seismic waves has progressed from the original weighted spring or oscillating pendulum seismometers to complex seismographs that track motion in three perpendicular directions over broad frequency bands and record them digitally. In addition to faulting events, seismometers also record ground motions caused by a wide variety of natural and man-made sources, such as the motion of cars and trucks on the highway, building demolition, mining explosions, lake level changes, fluid withdrawals, cavern collapse, sonic booms, hurricanes and ocean waves crashing on the beach. Instrumentation improvements have provided enhanced recording sensitivity. The difference in quality of earthquake data from today's seismometers to those from 20 or 30 years ago should be considered when viewing historical earthquake data. Knowing the details of the seismometer used to acquire the data is beneficial since some older seismometers are still in service. APPENDIX L: discusses the various earthquake databases.

The recordings of earthquakes must be analyzed to determine the origin (latitude, longitude and depth) of the faulting. At least three separate locations of seismograph readings are needed to locate the surface position (epicenter) of the earthquake. A model, with the major earth velocity layers (described below), is used to separate the signals received into the different wave types to determine the depth at which the earthquake occurred (hypocenter). Seismic wave velocity is a function of rock porosity, fluid saturation, compaction, and overburden pressure, or in rock mechanics terms, the elastic modulus, permeability, and density. For earthquake modeling, the Earth (surface through mantle) is divided into thick layers; waves that travel through a layer are assigned a velocity that is uniform within the layer, but that velocity differs from layer to layer. For exploration seismic modeling, a much more refined velocity model is needed to focus on the target interval.

Seismometers in the permanent monitor grid in most of the continental United States are spaced up to 200 miles (300 km) apart. With this spacing, the system is capable of identifying events down to approximately M3 or M3.5, although in some areas the system sensitivity may extend to M2.5. In tectonically active areas, such as the continental western margin and New Madrid Seismic Zone, the seismometer spacing is closer, resulting in more accurate earthquake locations. Additionally, closer grid spacing generally allows measurement of events of smaller magnitude.

Since 2007, the IRIS EarthScope Transportable Array has travelled systematically across the continental United States. The deployment of this array has led to an increase in lower-level seismic event detection that was not previously possible. This array includes seismometers spaced every 70 km, and is capable of picking up events down to around M1. Subsequent research reports have concluded that the added modern seismometer density provides significant additional information, including improved recording and quality for earthquake

hazard analysis, and identification of earthquake swarms and clusters (Lockridge et al., 2012; Frohlich, 2012). Consequently, the number of recorded seismic events over time is partly a function of the seismometer array density and instrument sensitivity.

The accuracy of earthquake focal depth determination is related to the seismometer grid density, seismometer quality, and the detail (quantity and accuracy) of the velocity model used to locate the event. Hypocenter depths are often reported using a default value for the geographic area of interest in the model. On initial event notifications, default depths will have similar depth uncertainties. For example, a depth of 5 km (16,500 feet) may have a vertical uncertainty between 3 and 5 km (10,000 to 16,500 feet). Generally, accurate focal depths (within less than 300 m (1,000 feet) vertically) are available only through special investigations, where the waves from the seismometers are individually analyzed with human assessment. The best depth estimates occur when a number of seismic instruments are within kilometers of the surface location of the earthquake.

According to the 2012 USGS glossary, the best located event has an uncertainty at the hypocenter of 100 m (300 feet) horizontally and 300 meters (1,000 feet) vertically. This small area of uncertainty may apply in California, but in the well constrained New Madrid Seismic Zone, Deshon (2013) noted, "Absolute earthquake location is a function of location algorithm, velocity model, event-station geometry and pick quality." Deshon found hypocenter locations moved up to 7 km in depth and 3 km geographically, by incorporating different phases in the model.

Natural resource exploration firms have used various seismic reflection techniques for years to better image the subsurface in three dimensions. The additional quality gained by increased recording density from a regional two-dimensional (2-D) survey to a tightly spaced three or four-dimensional survey is remarkable. Passive seismic recordings are now in use either in active seismic areas or producing hydrocarbon fields with microseismicity to further refine the subsurface structure (Shemeta et al., 2012; Verdon et al., 2010; Martakis et al., 2011).

There are a series of different seismic event reports available from the USGS Earthquake website that fit different needs. Initial seismic event reports, generated within hours of the event, are designed to help with emergency response and are preliminary, with a large location uncertainty. Later reports generally have increased accuracy (in both magnitude and location), as more information has been incorporated and the standard event modeling has been applied.

EARTHQUAKE RISK

Seismic hazard represents the potential for serious seismic events, whereas earthquake risk is the potential for damage to people and facilities that may result from the earthquake. Induced

seismicity risk evaluates the potential for triggering an earthquake by altering conditions and initiating movement along a pre-existing, optimally oriented fault.

In 1977, Congress passed legislation to reduce the risks to life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program primarily designed to promote safe surface designs. As a result, USGS provides hazard maps used in risk assessments (APPENDIX M:). Hazard typically relates to magnitude whereas risk is associated with earthquake intensity. The intensity scale describes either how strongly the earthquake was felt or the degree of damage it caused at a specific location. A strong earthquake yields different levels of intensity based on distance from the epicenter and local surface geology, as well as the size of the earthquake. The USGS has instituted a "Have you felt it?" campaign to increase the epicenter location accuracy and to better define the intensity according to the non-quantitative Modified Mercalli Intensity Scale.[24] The Modified Mercalli Intensity Scale is used to map surface effects for a given earthquake with scale increasing with amount of damage. The Modified Mercalli Intensity Scale has 12 levels of intensity that range from imperceptible shaking to catastrophic destruction. The scale is based on observed effects and does not have a mathematical basis.

Surface and near-surface designs of structures are developed by engineers for projects ranging from water reservoirs to deep tunnel construction to horizontal well drilling. These structures are designed to withstand existing and potential stress, including seismically created stress from strong ground motion (Pratt et al, 1978; Roberts, 1953; Schmitt et al., 2012; Coppersmith et al., 2012).

To understand how risk varies for surface versus subsurface structures, consider first the intensity difference. Seismic waves at the earth's surface cause the greatest structural damage through a combination of amplitude and duration of shaking. For the most damaging earthquakes, the earth's surface moves very similarly to the surface of the ocean in a storm. Consider the difference in motion on a ship at the top of the mast, main deck, and sea anchor. In simplistic terms, this would correspond to the top of a high-rise building, ground-level structures, and deep structures such as a wellbore. Accordingly, a wellbore cemented through various layers of rock will undergo little motion.

Serious damage from large earthquakes occurs not from the primary fault motion, but from the secondary processes: landslides, subsidence, liquefaction, and surface fault displacements, combined with failure of engineered structures not designed for strong ground motion. High risk

[24] http://earthquake.usgs.gov/learn/topics/mercalli.php

is also present along coastlines from submarine earthquakes, or on large bodies of water, in the form of large waves or erratic waves crashing on shorelines (tsunami and seiche, respectively).

Most reports cover damage at or above surface ground level. The USGS compiled a summary of earthquakes, over M4.5, in the United States between 1568 and 1989 (Stover and Coffman, 1993), describing any damage that was observed, including in shallow and deep wells. The report covered tens of thousands of earthquakes. Forty-three wells were mentioned predominantly in connection with temporary turbidity or fluid level changes with fewer than ten damage reports. Most of these wells were shallow water wells. Damage was frequently minor, from a tile falling off to a crack in the surface casing. The most applicable section was for the May 2, 1983, earthquake in Fresno County, California: "In the oil fields near Coalinga, surface facilities such as pumping units, storage tanks, pipelines and support buildings were all damaged to some degree.... Subsurface damage, including collapsed or parted well casing, was observed only on 14 of 1,725 active wells."

UIC programs require that operators run a mechanical integrity test after an injection well workover (when operators repair casing or replace tubing and/or packer). The workover report typically lists the problem repaired, but does not identify the cause of the problem. UIC program directors also have discretionary authority, in cases of earthquakes, to require additional measures such as mechanical integrity testing, as necessary to protect USDWs.

SEISMOLOGY AND ROCK MECHANICS GLOSSARY

Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS). Earthquakes resulting from human activities will be called induced earthquakes in this report.

Earthquake hazard is anything associated with an earthquake that may affect the normal activities of people. This includes surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunamis and seiches. (http://earthquake.usgs.gov/learn/glossary/, downloaded 5/22/13)

Earthquake intensity is a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several scales exist, but the Modified Mercalli scale and the Rossi-Forel scale are most commonly used in the United States. There are many intensity values for an earthquake, depending on where you are, unlike the magnitude, which is a single value for each earthquake (USGS).

Earthquake magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph with an accompanying correction for the distance from the earthquake to the seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (M_L), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (M_s), (3) body-wave magnitude (m_b), and (4) moment magnitude (M_w). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (M_w) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types.

Earthquake risk is the probable building damage, and number of people that are expected to be hurt or killed if a likely earthquake on a particular fault occurs. Earthquake risk and earthquake hazard are occasionally incorrectly used interchangeably. (http://earthquake.usgs.gov/learn/glossary/, downloaded 5/22/13)

Epicenter is the point on the earth's surface vertically above the hypocenter (or focus) point in the crust where a seismic rupture begins. NEIC coordinates are given in the WGS84 reference frame. The position uncertainlty of the hypocenter location varies from about 100 m horizontally and 300 m vertically for the best located events, those in the middle of densely spaced seismograph networks;, to tens of kilometers for events in large parts of the United States.

Hypocenter, aka focus, is the 3-D location of the earthquake source, i.e., latitude, longitude and focal depth below ground.

Period is the inverse of frequency, or the time interval for one full cycle of the wave. It is equivalent to the wavelength (distance) divided by speed. This is the measure of time at the seismometer, from one peak to the next.

Radius of the earth is roughly 6,371 km (polar 6356.8 km and equatorial 6,378 km) (http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html, downloaded May 22, 2013), with the radius of the core 3,485 km.

Rock mechanics is the study of the mechanical behavior of rocks, especially their strength, elasticity, permeability, porosity, density and reaction to stress (dictionary.com).

- Elastic rock is able to return to their original shape after the deforming stress is removed.
- Plastic rock is where non-reversible changes occur within the material itself through inter-granular gliding, rotation or recrystallization, not through rupture.

- Ductile rock is one capable of behaving elastically until it exceeds some threshold load where it may behave plastically, undergoing permanent change without breaking.

Seiche is the sloshing of a closed body of water from earthquake shaking. Swimming pools often have seiches during earthquakes.

Shear is an action or stress, resulting from applied forces, which causes or tends to cause two contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact (Webster, 1946).

Shear stress is the stress component acting tangentially to a plane, (Webster, 1995).

Shear zone is a portion of rock mass traversed by closely spaced surfaces along which shearing has occurred and within which rock may be crushed and brecciated (Webster, 1995).

Stress is the physical pressure, pull, or other force exerted on one thing by another (dictionary.com), or the force of resistance within a solid body against alteration of form (Webster, 1995) such as:

a. The action on a body of any system of balanced forces whereby strain or deformation results.

b. The amount of stress, usually measured in pounds per square inch or in Pascals.

c. The load, force or system of forces producing a strain.

d. The internal resistance or reaction of an elastic body to the external forces applied to the body.

e. The force acting on an area.

Strain is deformation of a body or structure as a result of an applied force (dictionary.com)

Torsion as used in mechanics (dictionary.com) is:

a. The twisting of a body by two equal and opposite torques.

b. The internal torque so produced.

Torsional stress is a shear stress on a transverse (direction at right angles to each other) cross-section resulting from a twisting action (Webster, 1995)

Wavelength is one cycle of the wave shown in distance units. It is equivalent to speed times period, or speed divided by frequency. This is measured peak to peak at a single time.

Wrench zone is .

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Petroleum engineering offers many approaches to assessing disposal well behavior and reservoir properties that may contribute to injection-induced seismicity. This appendix provides more details on the petroleum engineering analyses and methods used for this project and analyses of the case studies. Other petroleum engineering methods or applications may also be useful to operators and Underground Injection Control (UIC) regulators in evaluating injection-induced seismicity. Collectively, petroleum engineering techniques may assist in a site-appropriate evaluation of the three key components for potential injection-induced seismicity.

Another aspect of the project included application of petroleum engineering techniques. Petroleum engineering methodologies provide core tools for evaluating the three key components of injection-induced seismicity as part of the site assessment process. A petroleum engineering-based site assessment may provide important details by quantifying reservoir transmissibility and by characterizing the flow pathways that together affect the amount and distribution of pressure buildup from disposal operations. Characterizing flow pathways helps operators and regulators determine whether the pressure buildup is being dispersed radially or in a preferential direction from the disposal well. Operational injection data analysis plots such as the Hall integral and derivative graph can be used to characterize flow pathways. The Hall integral and derivative responses at some of the case study wells suggest hydraulic communication with a boundary (i.e. an offset well or fault) at some unknown distance from the

well. An analysis of available operational data may not provide conclusive proof of induced seismicity, but may identify wells warranting additional investigation. No single approach or technique can provide definitive proof that an injection well caused seismicity.

WHAT ARE PETROLEUM ENGINEERING CONSIDERATIONS?

Site assessment considerations in the decision model focus on three key components for the occurrence of injection-induced seismicity: the presence of a Fault of Concern, disposal interval pressure buildup, and a reservoir flow pathway able to transmit sufficient pressure buildup from the disposal well to the fault. All three components are necessary to induce seismicity. Petroleum engineering methods address pressure buildup and the pathway present around the disposal well as well as characterizing reservoir behavior during the well's operation. Analysis of the well's operational behavior is particularly useful after area seismic activity has occurred. Petroleum engineering approaches coupled with geologic and seismologic data may also provide area fault information. These methodologies can provide both quantitative and qualitative descriptions of the disposal wellbore and reservoir conditions. For example, some of the case study wells reviewed experienced specific Hall integral and derivative responses that corresponded to area seismic events. The Hall integral and derivative responses at these wells suggest hydraulic communication with a boundary (i.e., an offset well or fault) at some unknown distance from the well.

Petroleum engineering methods encompass well construction, well completion, well operations and reservoir characterization to evaluate and optimize well performance. In this report, these fundamental petroleum engineering methods were applied to evaluate disposal wells in the four case study areas using available data. The WG assessment process examined injection well operational and reservoir behavior in regard to seismic event activity, with a view toward assembling a toolkit of useful techniques.

PETROLEUM ENGINEERING INFORMATION COLLECTION

Information collection focuses on disposal wellbore details and how these parameters might contribute to injection-induced seismicity. Well construction and completion conditions, the well's injection profile (where the injected waste is emplaced), and injection rate determine bottomhole injection pressure and conditions that may impact the zonal isolation of the injected fluids. Applications of these aspects are detailed below.

UIC Class II disposal permits typically include disposal well construction and completion data such as the well completion date, casing and tubular dimensions and depths, cementing records, total well depth, packer depth and type, waste density, completion interval(s) and type (e.g., open-hole, screen and gravel pack, or perforated), and initial pressure prior to disposal. Detailed

knowledge of the well layout is necessary for assessing the isolation of the disposal zone through cemented casing, geological confining layers, location of the disposal zone relative to basement rock, and whether the disposal zone includes multiple intervals or is focused on a single interval.

Knowledge of the waste density and wellbore tubular dimensions, coupled with the injection rate, enables calculation of an operating bottomhole pressure (BHP) by accounting for the hydrostatic pressure of the fluid column and friction pressure loss of the tubing. This calculation is particularly useful for converting surface pressure injection history to bottomhole conditions. The operational BHP gradient trend can be compared against the estimated or measured fracture gradient for the disposal zone to assess whether injection-induced fracturing is a concern. Static BHPs can be estimated from the fluid density combined with either the static fluid level or surface pressure.

Cased hole and production logs can also provide useful information on the wellbore condition to assess injection operation conditions. Production logging data may supplement geologic data by providing additional insight about out-of-interval fluid movement and vertical pressure dispersal. Cased hole logs, such as cement bond logs, can identify properly or poorly cemented portions of the injection casing. Production logs (radioactive tracer surveys, flowmeters, temperature, oxygen activation and noise logs) provide information about injection profiles, zonal isolation and upward and downward fluid channeling. The wellbore injection profile shows where fluid is entering the formation, which in turn controls the reservoir pressure buildup response. Annular pressure tests and production logging can also confirm well mechanical integrity if this is a concern following area seismic activity.

Temperature logs typically require the well be shut-in for 36 to 48 hours prior to running the log so the temperature differential between the injected fluid and reservoir temperature can be effectively measured. Radioactive tracer tests use slug chases or velocity shots to evaluate the injection profile in the well. The radioactive ejector tool has limited capacity and may require multiple trips in and out of the well to reload when profiling large disposal zones. Flowmeters, such as spinner surveys, are typically less effective in large-diameter casing or open-hole intervals. Production logs are routinely used for Class I hazardous waste injection wells, but are not typically required for Class II disposal wells. Several of the case study wells had long vertical open-hole completions, but no assessment of the injection profile. However, in the Ohio case study, a production log was conducted to assess the portion of the disposal zone receiving fluid.

UIC operational compliance case study data generally included monthly injection volumes with maximum and/or average surface injection pressures. Using this data along with the well construction and completion information, the WG assessed well construction conditions and calculated operating bottomhole injection pressures for each case study well. The calculated

bottomhole operating pressures were then used in the petroleum engineering approach analyses.

Available Class II Data

The most common data available for Class II disposal wells are injection rates/volumes and injection tubing pressures. Such data are routinely reported as part of both EPA direct implementation and state UIC Class II program requirements. BHPs, more suitable for evaluating reservoir conditions, are not as readily available. The frequency for reporting injection volumes and pressures varies among regulatory agencies and depends on site circumstances. Although less common, pressure transient test data are occasionally available.

The following data types may be available for Class II disposal wells:

UIC monitoring data commonly reported:

- Injection rates or volumes
- Surface tubing pressures

UIC permit applications data commonly submitted:

- Well construction
    - Tubular (tubing/casing) dimensions and depth
    - Cementing information
    - Completion type and interval
- Reservoir information
    - Gross and net injection zone thickness
    - Porosity
    - Name and description of disposal zone and overlying confining zones
    - Bottomhole temperature
    - Initial static BHP
- Reservoir and injection fluids
    - Specific gravity
    - Fluid constituent analysis

Though less common, these pressure test measurements may also be available:

- Falloff/injectivity test for reservoir characterization and well completion condition assessment
- Step rate test to determine formation fracture gradient
- Static pressures to measure initial pressure and static reservoir pressure change during well operations

Petroleum Engineering Analysis of Operational Data

The WG conducted petroleum engineering analyses of any available data sets from the case study wells for correlation with reservoir behavior and geologic environment. The petroleum engineering approach couples reservoir rock and fluid properties with time, pressure and injection rate data from well operations to describe and predict reservoir behavior. Analysis of disposal well operating data and well testing, such as pressure transient tests, can provide details about the disposal zone reservoir pathway and the completion condition of the well. Operating injection rates and pressures are typically collected as part of the permitting compliance activity and consequently are more readily available than pressure transient tests. Completion conditions reflect conditions at or near the wellbore, while reservoir characteristics describe the disposal zone away from the well. For example, a well that has been fracture-stimulated displays a different response than an unfractured well.

Reservoir characterization assesses the injection formation flow patterns, the formation's capacity to transfer pressure responses, and the completion condition of a disposal well. Identifying anomalous reservoir behavior through such analyses and then correlating the results with geoscience data may suggest relationships between injection well pressure response and induced seismic activity. The petroleum engineering approach was incorporated into the case study analyses.

Operational Data Plots and Analyses:

Both operating data and pressure transient data shown on appropriate plots represent "pictures" of mathematical responses that can be fit to reservoir models. These models qualitatively and, in some cases, quantitatively characterize well completion and performance conditions, reservoir flow geometry and, in limited cases, reservoir geology. Graphs of reported injection volume and operational pressures reflect reservoir behavior over time. Longer periods of operational data (typically in months or years) allow a longer distance, though less refined, look into the reservoir than a shorter timeframe pressure transient test.

Graphical format for the petroleum engineering analytical plots varies and may range from tandem linear axes to dual log axes, depending on the type of analysis performed. The graphs may display certain patterns or quantitative values which inform the reservoir analyst as to what type of reservoir flow characteristics are present or identifies changes in reservoir behavior over time. Reservoir characteristics identify the type of disposal zone reservoir pathway present and indicate its tendency to dissipate pressure buildup, either radially or in a preferential direction. Hence, the data can be used to "describe" the reservoir pathway.

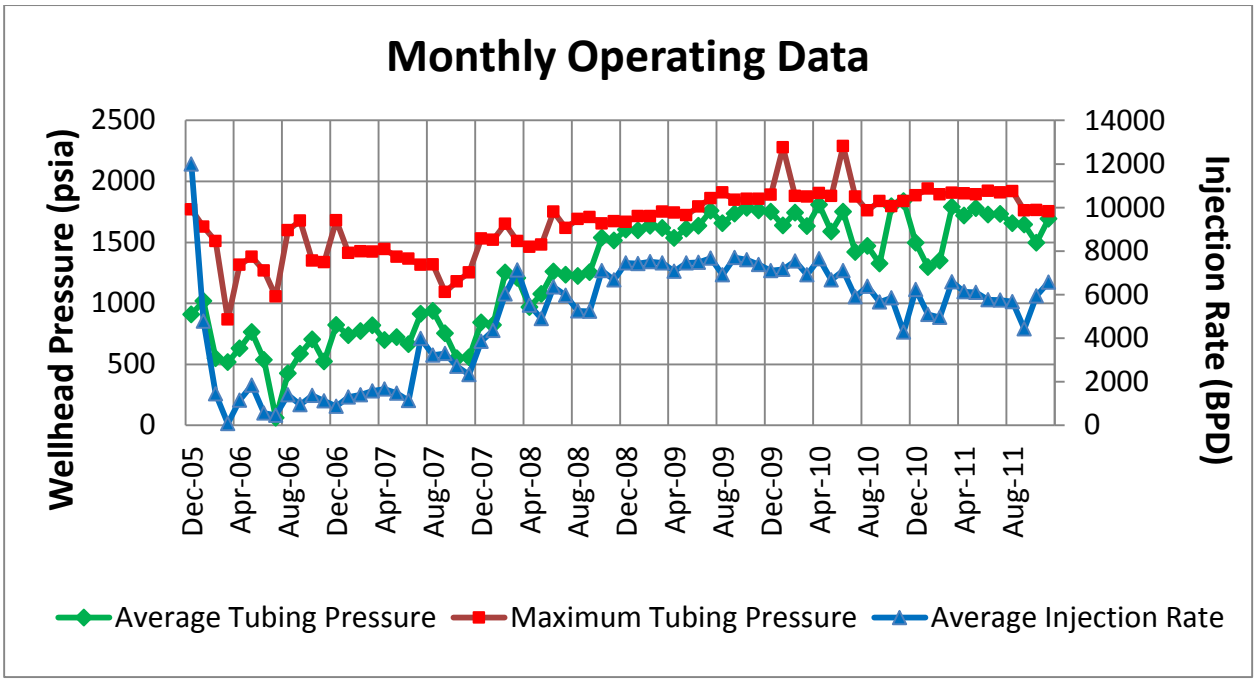
Operational data can be analyzed using the steady state radial flow equation, in the form of the Hall integral and its derivative, while pressure transient tests are analyzed using solutions to the radial diffusivity equation. Operational data include both injection rate and pressure information, but actual data reported can vary depending on the regulatory agency requirements. For example, injection volumes may be reported with daily, monthly, or quarterly frequency. UIC programs may require reporting of injection pressure a number of ways, such as a maximum value and a monthly average or as monthly minimum and maximum values.

For best applicability, surface pressures should be converted to bottomhole conditions prior to performing a Hall plot analysis. This conversion requires the analyst to account for friction pressure loss with a correlation, such as Hazen-Williams (Westaway and Loomis, 1977; Lee and Lin, 1999), based on the tubing specifics and injection rates. The hydrostatic pressure from the fluid column must be added to the surface pressure as part of the bottomhole pressure calculation. The reporting frequency for injection rates can also impact the quality of the analysis. Plots, calculations and analyses associated with operational data are summarized below:

Operating Rates and Pressures Overview Plot

- Overview of surface pressures and injection rate or volume plot (Figure D-1)
    - Cartesian (linear) plot of surface injection pressure and rate/volume versus date
        - y-axis primary: average and maximum wellhead (surface or tubing) pressure
        - y-axis secondary: average injection rate (barrels per recording time period)
        - x-axis: date (based on recording timeframe, e.g., daily, monthly, quarterly)

FIGURE D-1: OVERVIEW PLOT OF MONTHLY OPERATING TUBING PRESSURES AND INJECTION RATES



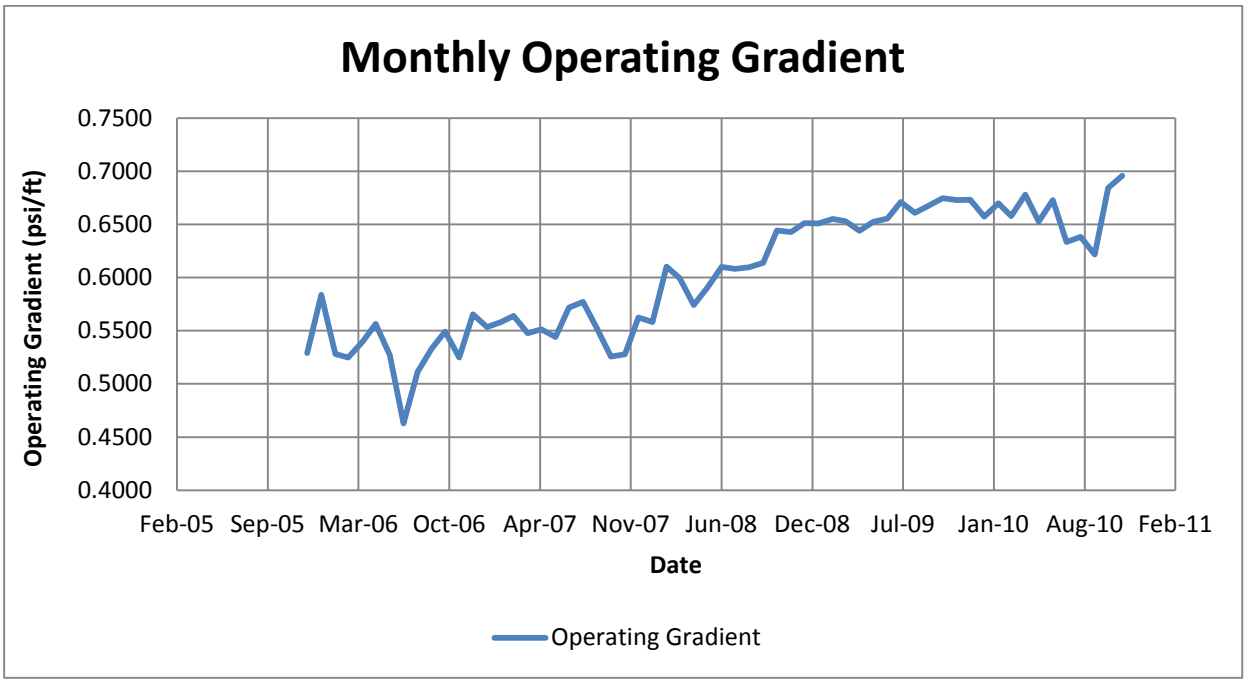
- Purpose
  - Identifies trends or large changes in pressure and/or injection rate/volume behavior
  - Provides a timeline of operational activity
- Challenges: Frequency of data reported, intermittent well use, quality of data
- Possible red flags
  - Maximum pressures nearing fracture pressure
  - Increased pressure with declining injection rates
  - Suspect data quality (e.g., repeating pressure value with varying injection rate)

Operating Pressure Gradient Plot

- Cartesian plot of the operating BHP gradient (Figure D-2)
  - The operating BHP can be measured or calculated
  - Calculated values are obtained by adding the hydrostatic pressure of the fluid column, based on the fluid specific gravity, to the surface tubing pressure and subtracting friction pressure loss
    - Calculate hydrostatic pressure of the fluid column:
      - (disposal fluid specific gravity) x (fresh water gradient) x (depth)
    - Specific gravity is obtained from a fluid analysis or is estimated
    - Friction loss is estimated using tubing dimensions and Hazen-Williams friction loss correlation (Lee et al., 1999; Westaway et al., 1977)

        - Tubing friction factor, C, is based on tubing type
        - Frequency of rates data impacts friction calculations
    - Operating pressure gradient equals operating BHP divided by depth (psi/ft)
        - Depth is the top of the completed interval or tubing depth
    - Cartesian plot of operating BHP gradient versus date
        - y-axis: operating pressure gradient, psi/ft
        - x-axis: date (based on recording timeframe, e.g., daily, monthly, quarterly)

FIGURE D-2: MONTHLY OPERATING PRESSURE GRADIENT PLOT



- Purpose
    - Compare operating pressure gradient to calculated or measured area-specific fracture gradients to confirm the disposal well is operating below fracture pressure
- Challenges
    - Conversion of surface pressure to BHP can be inaccurate
    - Variations in injectate specific gravity introduce uncertainties in calculation of the hydrostatic fluid column
        - More of a concern in commercial disposal wells
    - Friction pressure estimates can be suspect, especially for wells with high injection rates through smaller diameter tubing
    - Frequency of rate data impacts friction calculations
- Possible red flags

- New fractures or fracture extension may occur if well is operating above the fracture gradient
- Tubing size and injection rates are not within appropriate ranges for calculating friction loss values

Hall Integral and Derivative Plot

The Hall integral has been used since 1963 (Hall, 1963; Jarrell et al., 1991). The Hall integral derivative evolved later, after the derivative approach was developed for well testing techniques (Izgec and Kabir, 2009). The Hall plot uses readily available operational data coupled with an estimate or measurement of the average static reservoir pressure prior to injection. This operational data is routinely recorded as part of UIC permit compliance.

The Hall plot represents a graphical integration of the steady state radial flow equation, which couples operating pressure and cumulative injection. Pressure values are calculated on a BHP basis for use in the Hall plot. The Hall plot is a numerical integration between the operating BHP and static (reservoir) BHP. This numerical integration yields a straight line trend for radial flow (Figure D-3). The integral (summation) serves to "smooth out" noise commonly present in injection operating data. The derivative is the running slope of the Hall integral plot. The derivative magnifies any slope change and tends to be much noisier than the Hall integral. Adding the derivative trend to the integral plot helps to more readily identify significant changes in disposal well behavior.

The Hall integral is an accepted petroleum engineering methodology that is easily calculated in a spreadsheet. The integral provides for a much longer observation period of the injection zone than is generally obtained with a pressure transient test. The well's pressure response corresponds to a greater investigative distance into the reservoir the longer the well operates. The Hall integral is a function of the pressure difference between injection and shut-in conditions weighted by operating time increments.

- Cartesian (linear) plot of Hall integral and derivative curves (Figure D-4)
  - Hall integral is a numerical integration between the operating BHP and static (reservoir) BHP
    - Tracks the change in operating pressure with time, compared to the initial static conditions
    - Cumulative or running summation of ($\Delta P * \Delta t$) as well operates
      - Values will increase with cumulative operation time
    - ΔP: Injecting BHP-static BHP calculated for each measurement
    - Δt: Time increment for measurements matched to ΔP calculation

- y-axis: Hall integral (H_I) = Cumulative ($\Delta P*\Delta t$) function, psi - time period
- y-axis: Hall integral derivative: $D_{HI} = (H_{i2}-H_{i1})/(W_{i2}-W_{i1})$
  - $(H_{i2}-H_{i1})$ represents difference between successive Hall integral values
  - $(W_{i2}-W_{i1})$ represents difference between successive cumulative injection values
- x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D-3: STYLIZED EXAMPLE HALL INTEGRAL PLOT WITHOUT DERIVATIVE

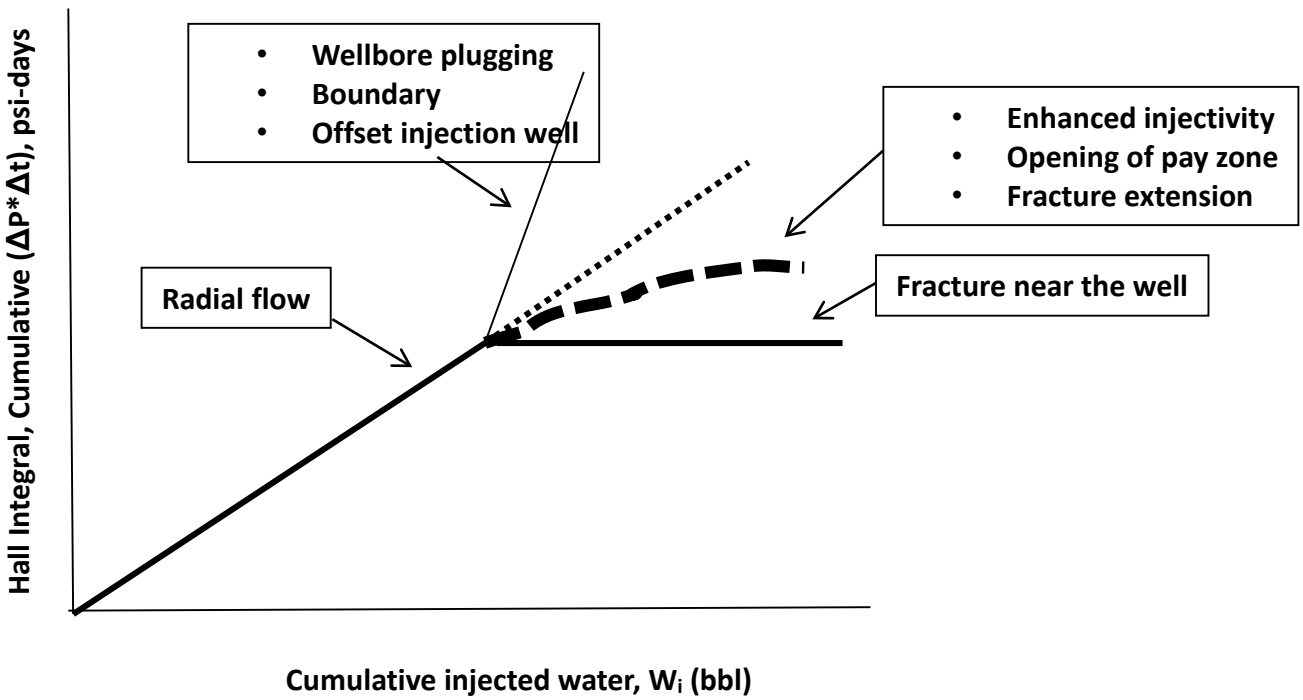
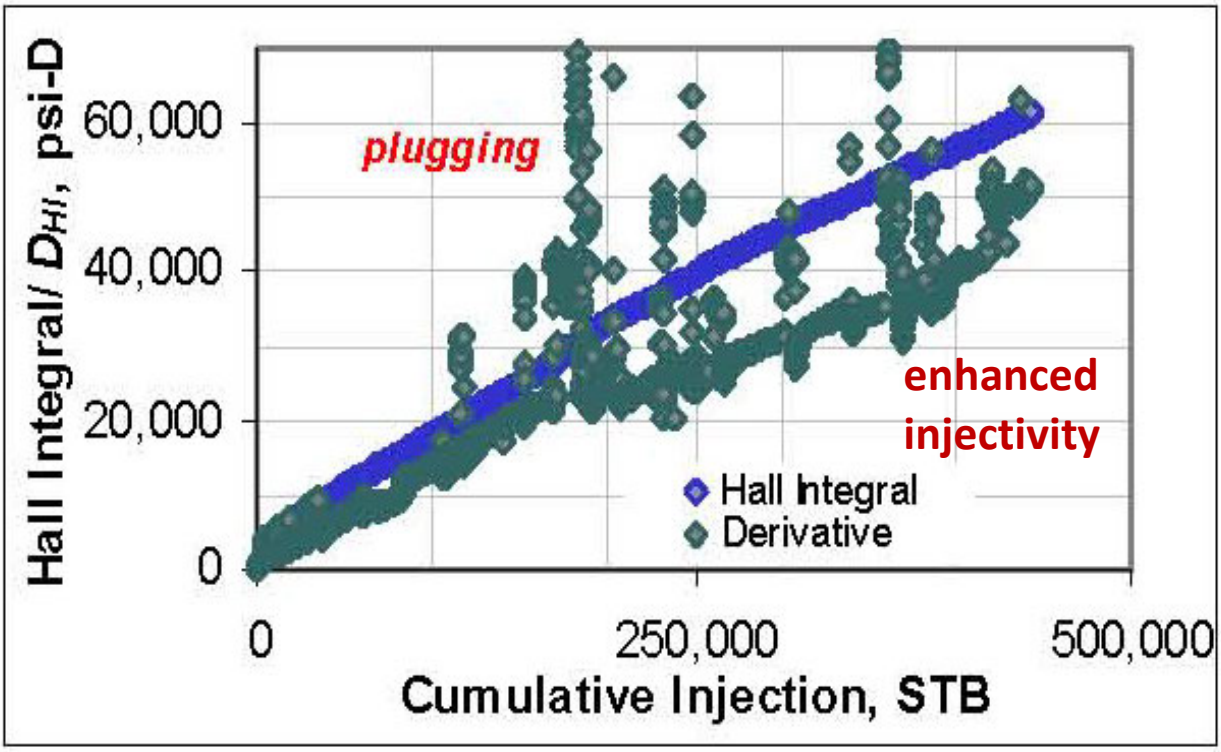


FIGURE D-4: HALL INTEGRAL WITH DERIVATIVE (MODIFIED FIGURE 1 FROM YOSHIOKA ET AL., 2008 WITH PERMISSION)



- Purpose
  - Evaluates injection well performance and reservoir flow behavior or changes in behavior over time
    - Slope change on the Hall integral trend reflects the pressure response as fluid moves radially from the disposal well
      - Slope indicates a well's completion condition or injection efficiency
      - Negative slope break associated with enhancement of injectivity
      - Positive slope break indicates reduced injectivity
      - No slope break (straight line) represents radial flow
  - Location on the plot of derivative (D_{HI}) relative to the Hall integral (H_I) also indicates the completion condition of the well
    - Highlights well behavior patterns
      - D_{HI} located below H_I indicates enhanced injectivity
        - Examples: Opening of new pay zone, fracturing, extension of existing fracture
      - D_{HI} superimposed on H_I indicates radial flow
      - D_{HI} above H_I suggests a decrease of injectivity
        - Examples: Near wellbore plugging, boundary, offset injection well

        - Hall derivative (D_{HI}) should always be a positive value if Hall integral (H_I) is increasing
- Challenges:
    - Frequency of pressure and injection monitoring affects quality of Hall derivative function and shape of plot
    - Requires an initial reservoir pressure
        - A measurement or estimate of the average initial static BHP is required
    - Conversion of surface pressure to BHP can be inaccurate
        - Friction pressure estimates can be suspect, especially for wells with high injection rates through smaller diameter tubing
    - Hall integral should increase as long as injection is occurring
        - If the static reservoir pressure estimate is too high, negative increments in the Hall integral calculation may result
    - Wells used intermittently require data manipulation to keep the Hall integral positive
- Possible red flags
    - Constant tubing pressure with varying injection volumes should raise questions about data quality
    - Positive slope change may be associated with a plugging at the well, boundary or offset injection well
    - Negative slope break may be associated with the opening of a new pay zone, fracturing, or extension of existing fracture

HALL INTEGRAL SENSITIVITY PLOTS

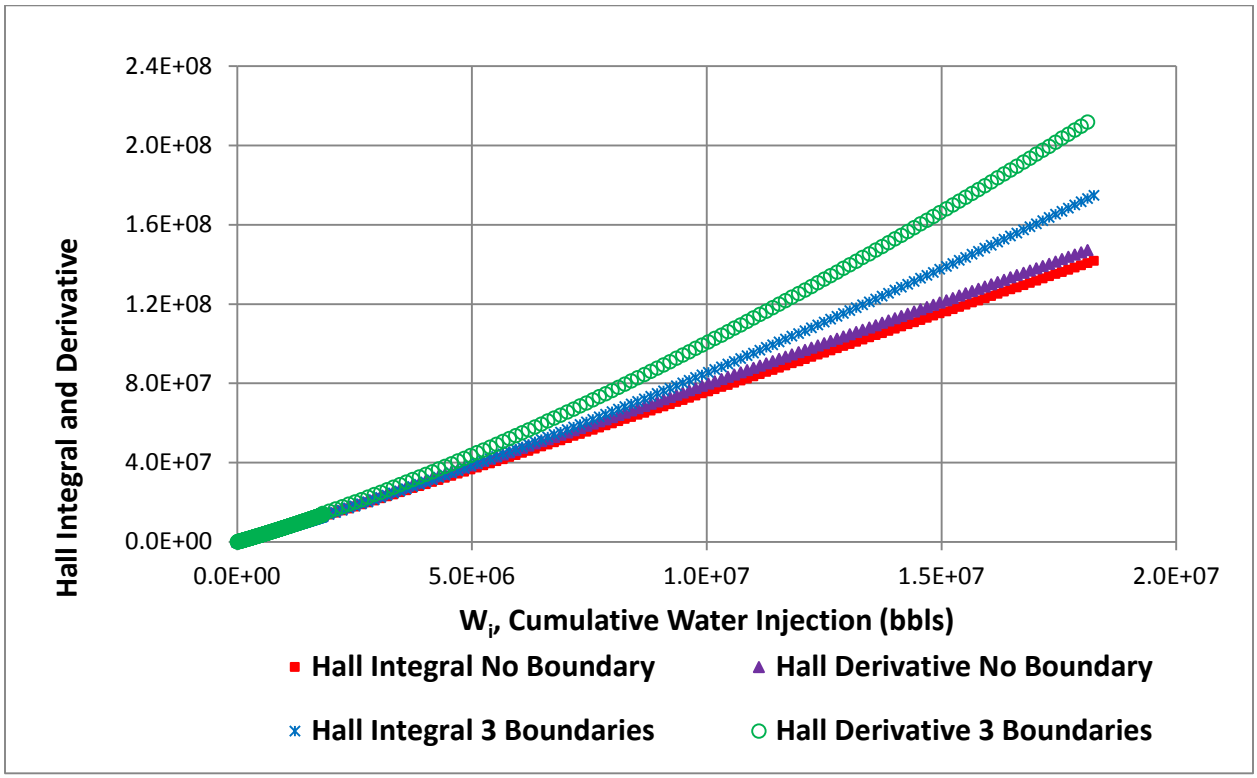
The WG conducted three sensitivity analyses to determine the Hall integral and derivative responses. The three sensitivity cases included (1) Hall integral response to a reservoir model containing boundaries, (2) the impact of the assumed initial pressure value used in the Hall integral calculation, and (3) the sensitivity of the Hall integral to the well operating timeframe.

Boundaries

Analytical models were set up using the PanSystem pressure transient software. One model included an infinite-acting radial flow reservoir and the second model contained a U-shape fault configuration representing three no-flow boundaries, each 2 miles equidistant from the injection well. Each model assumed continuous injection of 5,000 barrels per day (BPD) for 10 years (with reservoir conditions of k=50 md, h=100 ft, μ=1 cp, r_w=.3 feet, c_t= $6x10^{-6}$ psi^{-1}, Φ= 20%, P_{init}=2000 psia). The modeled pressure responses represented bottomhole conditions and a skin factor of 0. The modeled pressures were then converted to Hall integral and derivative plots.

- Hall integral and derivative plot with and without boundaries (Figure D-5)
  - y-axis:
    - Hall integral (H_I) = Cumulative ($\Delta P*\Delta t$) function (psi-time period)
    - Hall integral derivative: $D_{HI} = (H_{i2}-H_{i1})/(W_{i2}-W_{i1})$
  - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D-5: HALL INTEGRAL AND DERIVATIVE RESPONSE FOR NO BOUNDARY AND 3 BOUNDARIES 2 MILES EQUIDISTANT FROM WELL



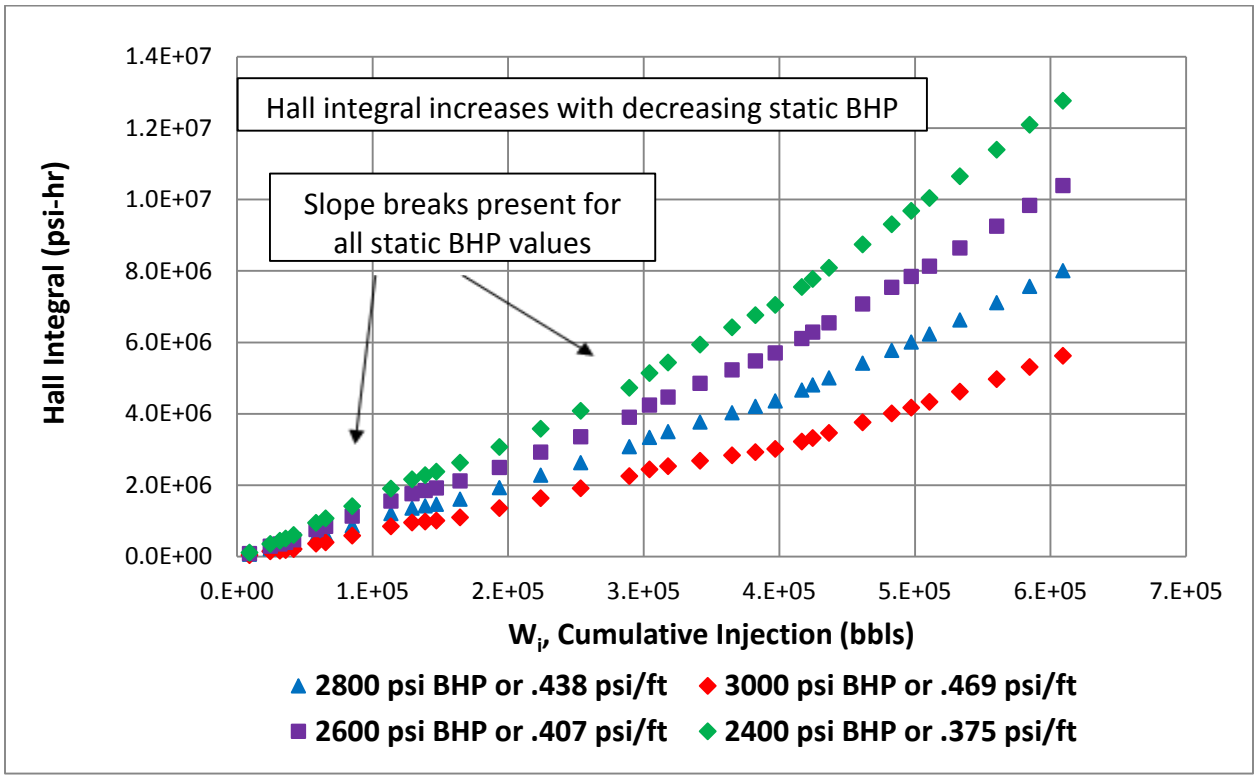
  - Purpose:
    - Determine Hall integral and derivative responses to known boundary conditions
    - Compared radial flow to U-shaped boundary conditions
      - Bounded system response causes Hall integral and derivative curves to have positive slope breaks
        - Derivative response located above Hall integral
        - Separation between the Hall integral and derivative increases with the number of boundaries encountered by the disposal pressure response
  - Challenges:
    - Boundary conditions may be unknown due to limited geologic information
    - Upswing may be from offset disposal activity and not associated with a no-flow boundary or fault

Initial Pressure

Sensitivity calculations were performed on each of the case study wells using a range of assumed static BHPs to explore the impact of static pressure assumptions on Hall plot behavior. Even with varied pressure assumptions, the overall slope change trend in each well was not impacted, but the degree of slope change did vary with the static pressure assumed. The WG concluded an incorrect static pressure would not critically alter the Hall plot qualitative meaning, though it would have a quantitative impact. For purposes of the case studies, the Hall plots were used for qualitative behavior assessment only.

- Linear plot of Hall integral with varying initial pressures (Figure D-6)
    - Checks the sensitivity to a range of original reservoir static pressures
    - y-axis: Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi- time period)
    - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D-6: HALL INTEGRAL INITIAL PRESSURE SENSITIVITY PLOT



    - Purpose:
        - Qualitative assessment of estimated static pressure estimate on character or shape of Hall integral trend

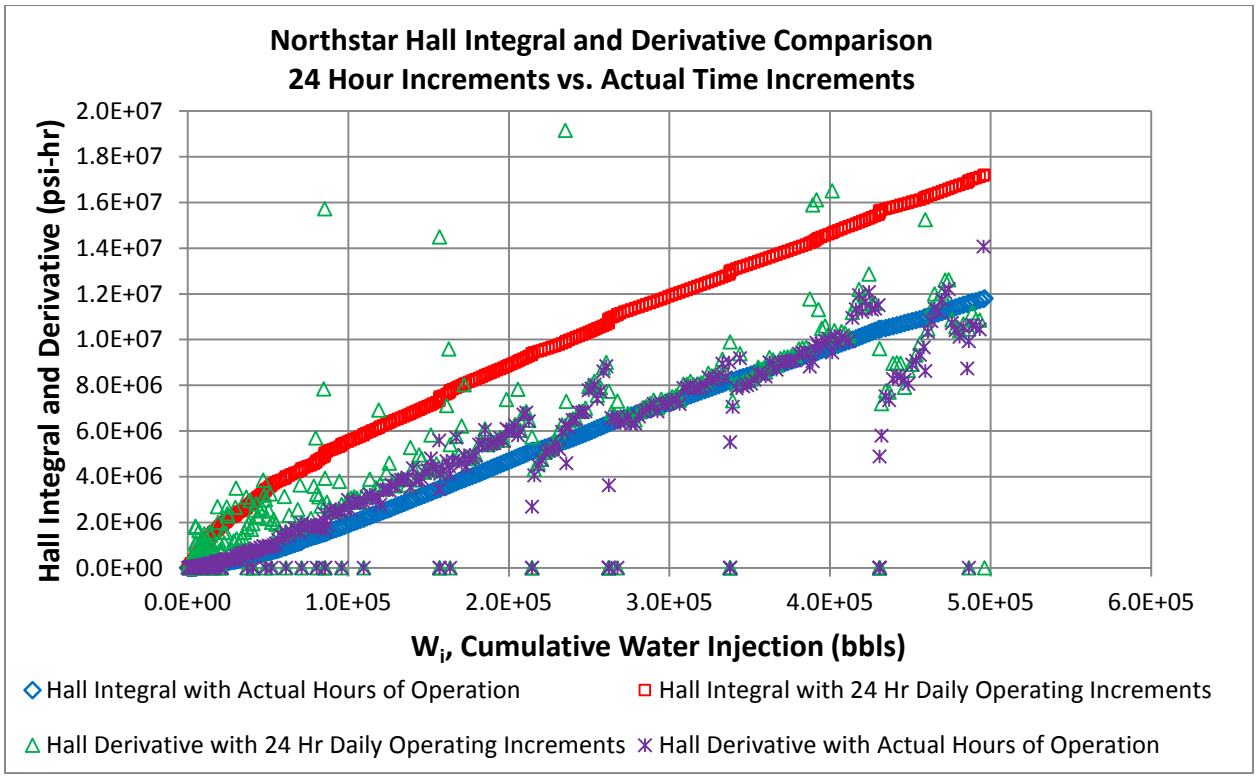
        - Hall integral becomes larger with decreasing initial static pressure due to increased pressure difference between injection and initial shut-in pressures
    - Challenges:
        - Negative increment in the Hall integral may occur if initial pressure assumption is too high
        - Degree of slope change in the Hall integral changes with the initial pressure assumption

<u>Hours of Operation</u>

Two different analyses were conducted for the Northstar case study well in Ohio. The initial analysis used quarterly reported volumes and assumed 24-hour continuous well operation. The second analysis was conducted using additional data that included specific hours of well operation and daily reported volumes and pressure for the same operational period as the initial data set. The second review resulted in a different Hall integral response. This sensitivity analysis is included to illustrate the difference in the Hall integral response based on the availability of details of the well operational history. As illustrated in Figure D-7, the initial analysis using 24-hour well operation indicated enhanced injectivity, while the analysis based on the actual time increments shows a combination of trends.

- Hall integral and derivative plot was calculated using different hours of operation (Figure D-7)
    - Used different hours of well operation to calculate the Hall integral and derivative
        - 24 hours of operation daily
        - Actual reported hours of operation
    - y-axis:
        - Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi- time period)
        - Hall Integral Derivative: $D_{HI} = (H_{i2}-H_{i1})/(W_{i2}-W_{i1})$
    - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D-7: IMPACT THE HOURS OF WELL OPERATION HAS ON HALL INTEGRAL AND DERIVATIVE CALCULATIONS



- Purpose:
  - Determine the impact that the hours of well operation have on Hall integral and derivative calculation for wells that do not operate continuously
    - Hall integral and derivative magnitudes and trends are affected by the time increment assumed for each injection volume reported
      - Too large a time increment value distorts the integral step size and corresponding derivative
      - Can present a misleading picture of shape of Hall integral and derivative response
- Challenges:
  - Actual hours of operation are not always reported

SILIN SLOPE PLOT

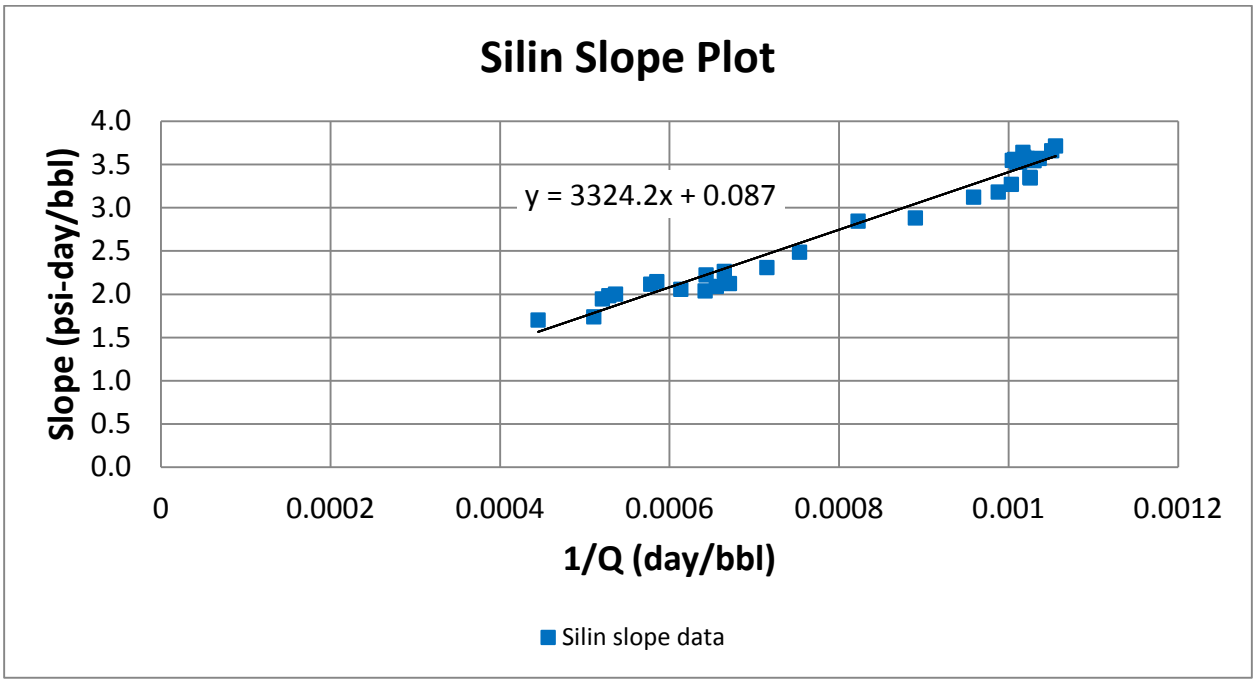
The Silin slope plot is used to determine average reservoir pressure around an injection well, using injection pressures and rates. Operational injection data are plotted on a linear plot of wellhead pressure divided by injection rate versus the reciprocal of the injection rate. The resulting data points are fitted to a best fit straight line with the line's slope yielding a mean reservoir pressure around the disposal well. The resulting average reservoir pressure can then

be used to develop a Hall plot. The Silin plot is designed as a method for monitoring reservoir pressure in active waterfloods and is only applicable to radial flow situations.

Silin slope plots were developed for each of the case study wells. In some cases, an estimate of average disposal reservoir pressure was available from fluid level data. The results of the Silin plots were compared against available measured pressures and generally predicted too high a reservoir pressure. The high Silin plot predicted pressures resulted in negative Hall integral increments; consequently, the Silin plots were not included in the case study analyses.

- Linear plot of injection well operating data (Figure D-8)
    - y-axis: Injection BHP divided by daily injection rate, P_{wf}/Q (psi-time period per barrel)
    - x-axis: Reciprocal of the injection rate, 1/Q (day per barrel)

FIGURE D-8: SILIN SLOPE PLOT



- Purpose
    - Developed as a modification to Hall plot analysis to determine mean reservoir pressure around the injection well
- Challenges:
    - Rate fluctuations in operational data can cause data scatter
    - Method is applicable at very early times during the infinite-acting period
        - Faults or fractures may introduce error in assumptions for applicability

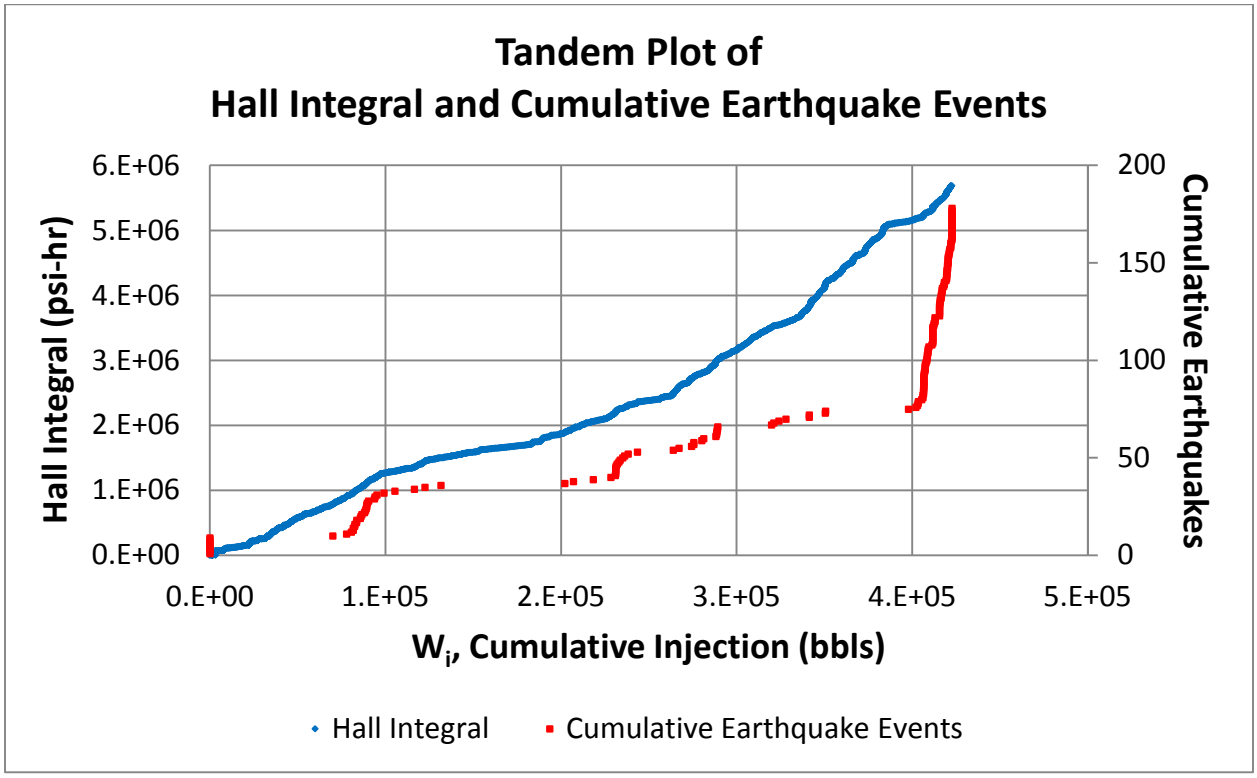
- Possible red flags
    - Data quality may contribute to a scattered plot
    - Unrealistically high static reservoir pressure

Tandem Plot Combining Hall Integral with Seismic Events

The tandem plot is designed to graphically compare the Hall integral response to a cumulative count of seismic events within a selected radial search area.

- Cartesian (linear) tandem plot (Figure D-9)
    - Plot of Hall integral and cumulative number of earthquake events versus cumulative injection
        - y-axis primary: Hall integral (H_I) = Cumulative ($\Delta P*\Delta t$) function (psi-time period)
        - y-axis secondary: Cumulative earthquake events (count)
        - x-axis: Cumulative injection volume, W_i (bbls)

FIGURE D-9: TANDEM PLOT OF HALL INTEGRAL AND CUMULATIVE EARTHQUAKE EVENTS



- Purpose:
    - Plot illustrates how injection well behavior and number of seismic events change with cumulative injection volume

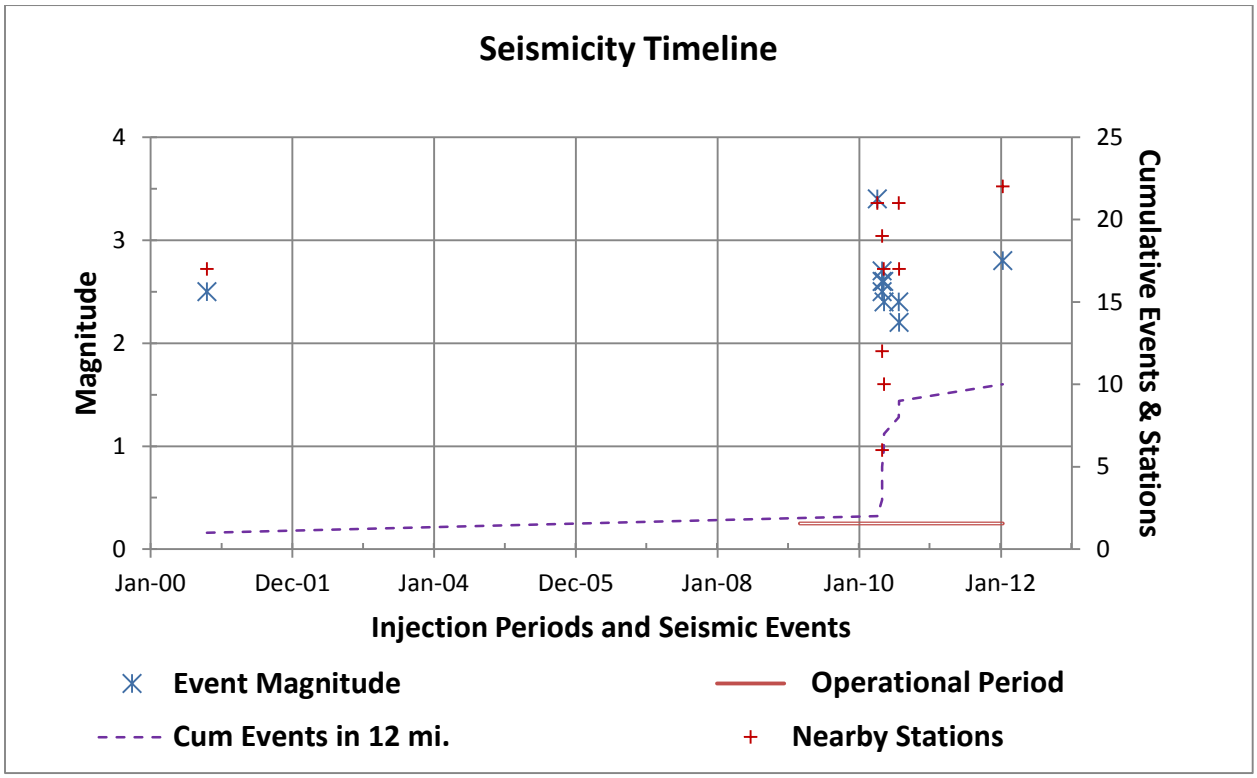
- Challenges:
    - Creating cumulative injection history for cumulative earthquake events
        - Selecting size of seismic monitoring area around disposal well
        - Acquiring seismic data from various databases
        - Linking earthquake events to cumulative injection based on event date
        - Increase in events may appear to be delayed owing to late deployment of additional seismometers
        - Deciding the lower magnitude limit to be included in count of seismic events
- Possible red flags
    - Correlation between injection well response (Hall integral slope change) and number of seismic events

SEISMICITY TIMELINE

The seismicity timeline plot was created to compare event magnitude, cumulative seismic events, number of seismometers and disposal well operational period. As the figure shows, once seismicity occurs, the number of seismometer stations may increase, to better record and locate the events.

- Seismicity timeline linear plot (Figure D-10)
    - Plot of the earthquake magnitude and cumulative number of earthquake events versus the operational period of the disposal well
        - Primary y-axis: Earthquake magnitude
        - Secondary y-axis: Earthquake cumulative events and number of recording stations
        - x-axis: date and disposal well operational period

FIGURE D-10: SEISMICITY TIMELINE PLOT



- Purpose:
  - Provide a common plot of seismic response and monitoring stations with period of disposal activity
- Challenges:
  - Selecting size of monitoring area around disposal well
  - Acquiring seismic data from various databases
  - Acquiring number of monitoring stations within the selected monitoring area
- Possible red flags
  - Correlation between operational period of disposal well and occurrence or number of seismic events
  - Seismic event background level prior to disposal well operations to determine if induced, i.e. if the background level was non-existent seismicity may be induced, whereas if there is no change in level, it probably is not.
  - Number of seismometers relative to number of seismic events

Overview of Pressure Transient Testing for Disposal Wells

Pressure transient theory correlates pressures and rates as a function of time and is the basis for many types of well tests, including both falloff and step rate tests. Pressure transient test analyses revolve around solutions to a partial differential equation, called the radial flow

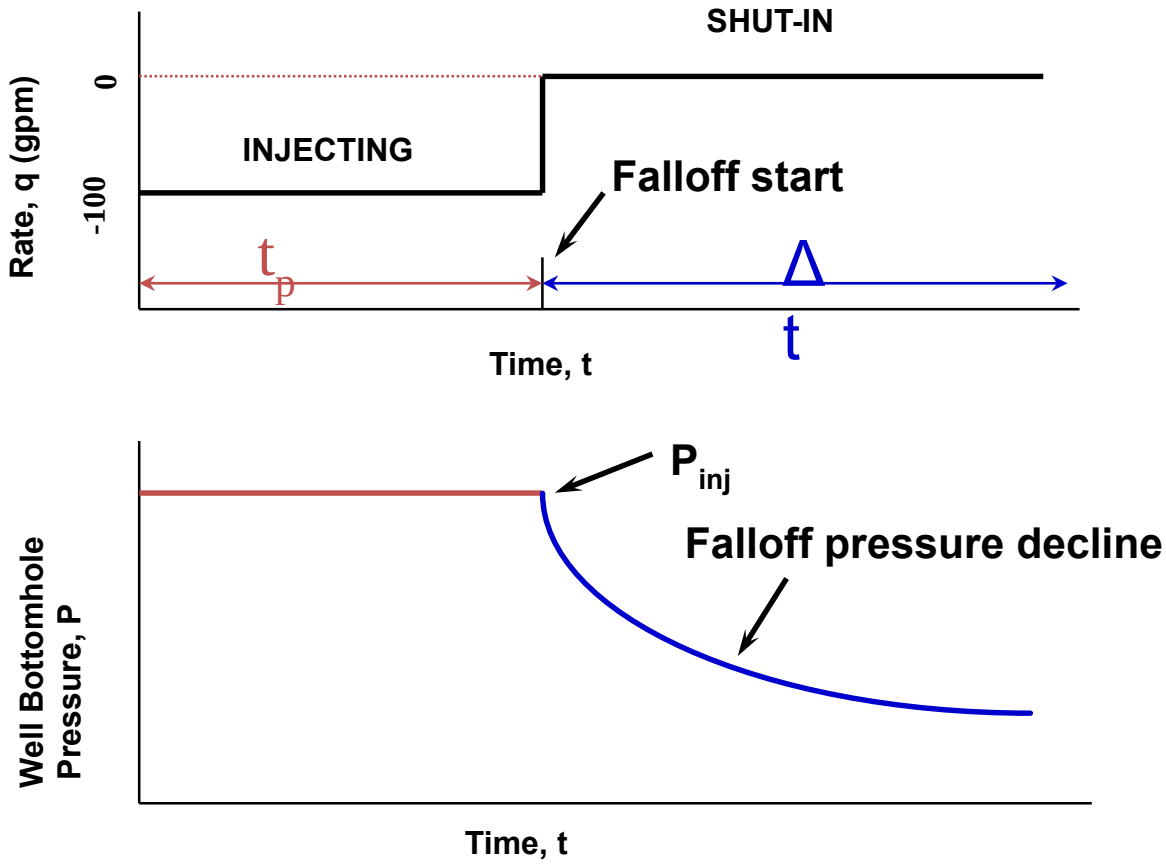
diffusivity equation. These solutions provide an injection well behavior model, provide a method for reservoir parameter evaluation and allow calculation of pressure and rate as a function of distance.

The most common solution used applies only to radial flow. However, this solution is not applicable in all geologic or well completion situations. By solving the diffusivity equation for boundary conditions to address the geological or completion situations present at the wellbore or in the reservoir, one can obtain mathematical solutions (type curves) specific to these situations. Since these reservoir model solutions are based on a differential equation, their "signature" is best presented in a log-log plot format.

Pressure transient tests provide a more refined look at the reservoir and well completion characteristics. Pressure transient tests are typically shorter in duration than the operational data analysis but are generally designed to provide a better reservoir description.

One type of pressure transient test commonly associated with a disposal well is a falloff test, which measures the pressure decline by recording the well surface pressure or BHP after the well is shut in. Falloff tests are to a petroleum engineer as seismic surveys are to a geophysicist. Pressure transient tests provide short and intermediate distance mathematical 'pictures' of the reservoir nature around the well when the data are analyzed against existing reservoir models. They are analogous to a short term pinging of the reservoir with sonar in the form of a pressure wave, whereas seismic surveys are acoustical 'pinging' of the reservoir. Both use some type of energy wave to probe through the reservoir much like sonar 'pings' the ocean or radar 'pings' the airways. In both instances, the reservoir response to the associated 'wave ping' is measured and analyzed. A falloff test sequence of events and pressure response is shown in Figure D-11.

FIGURE D-11: FALLOFF TEST SEQUENCE OF EVENTS AND PRESSURE RESPONSES



Another type of pressure transient test commonly associated with a disposal well is a step rate test. Step rate tests are a direct method of estimating fracture pressure and fracture gradient (formation parting pressure) of the disposal zone. Step rate tests can be analyzed for both fracture gradient and reservoir characteristics. Step rate testing consists of a series of constant rate injection steps with each step being maintained for an equal duration of time as shown in Figure D-12, with corresponding pressure increases as illustrated in Figure D-13. Ideally, the injection pressure should be stabilized at the end of each rate step.

FIGURE D-12: STEP RATE TEST RATE SEQUENCE

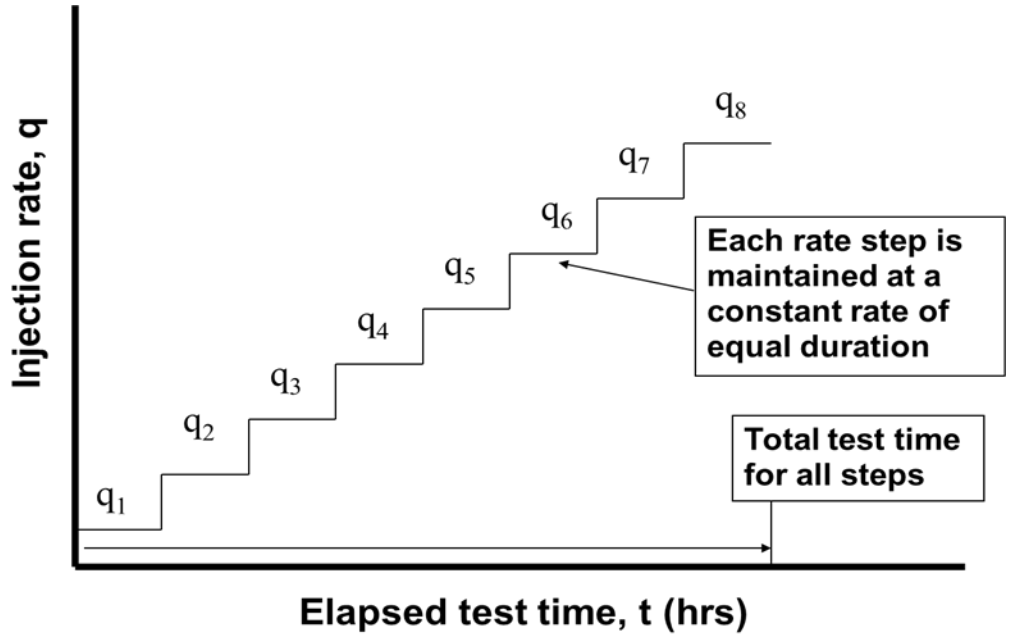
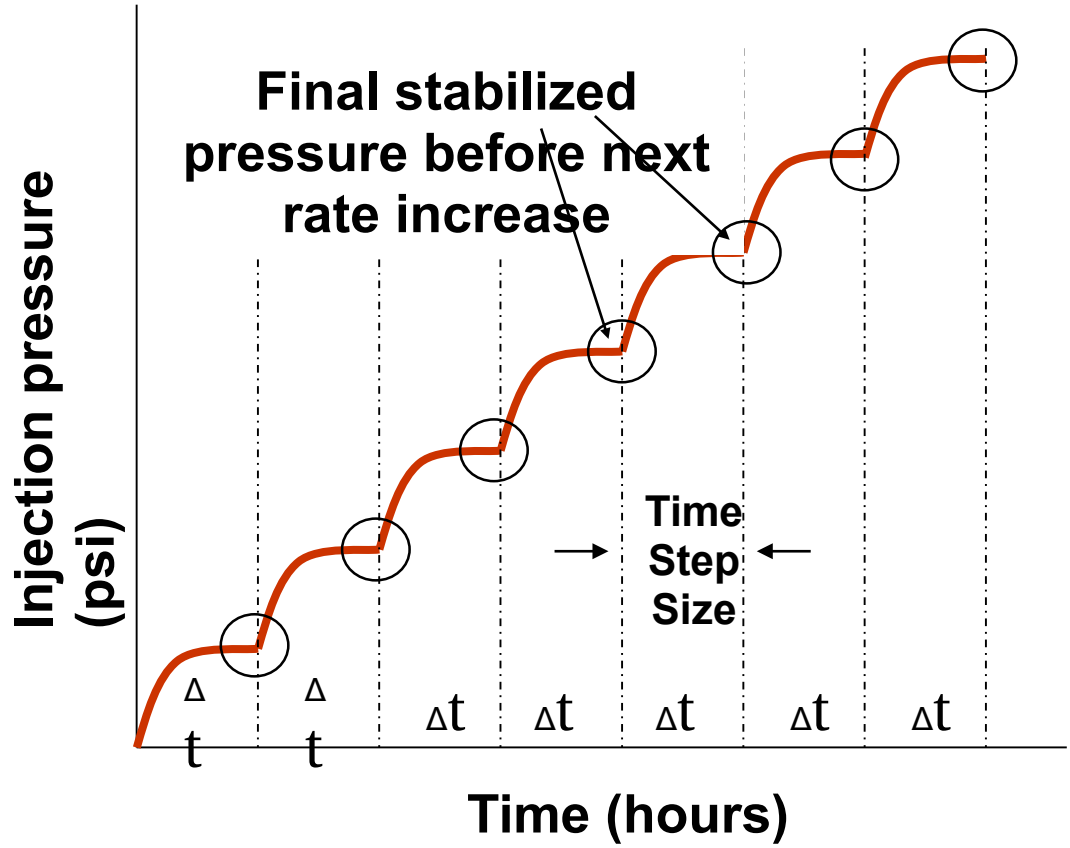


FIGURE D-13: STEP RATE TEST PRESSURE SEQUENCE



Analysis of Disposal Well Pressure Transient Tests

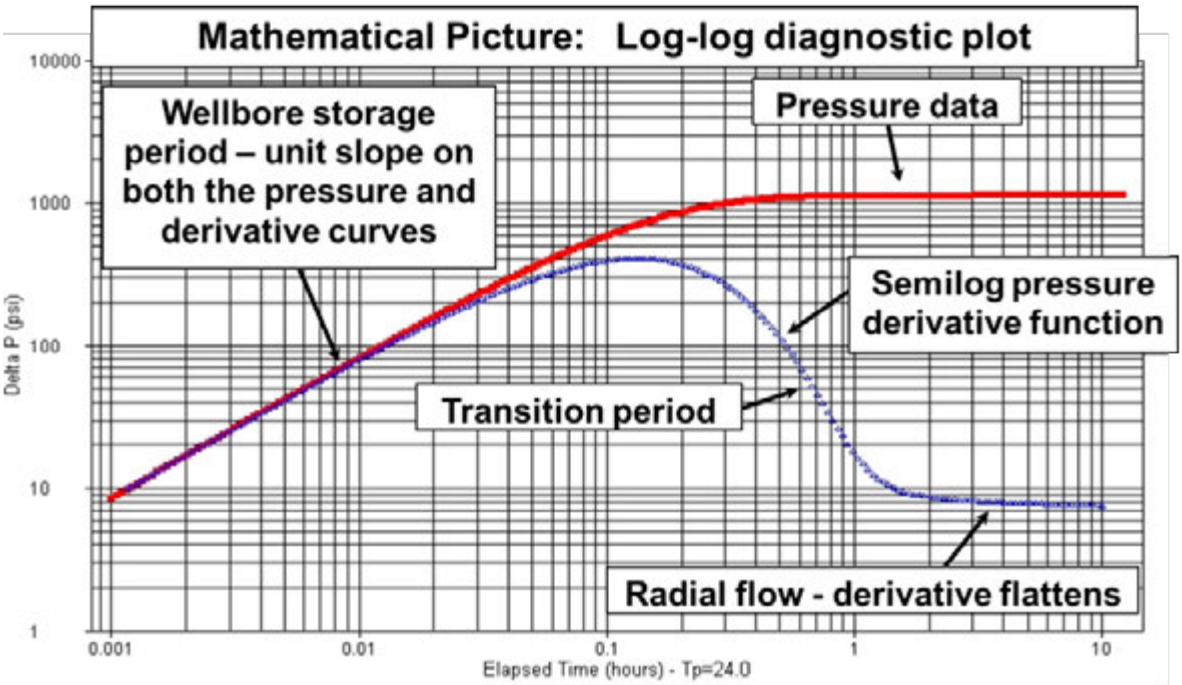
Analysis of both falloff and step rate tests involve pressure transient analysis techniques. Common methodology can be applied to each of these two tests. Falloff test analysis typically requires specialized software. Step rate tests can be analyzed using a spreadsheet, though a more detailed analysis may also necessitate the use of specialized software. Details relating to the analysis of each type of test are provided below.

Falloff Testing

The first step in analyzing a falloff test is plotting the data in a format that allows for comparison against the known reservoir model solutions to the unsteady state radial diffusivity equation. To compare site-specific test data to these solutions requires plotting the actual data in a log-log plot format, as shown in Figure D-14. The log-log plot becomes a useful diagnostic tool for detecting patterns of behavior at the well and into the reservoir. These patterns indicate the presence of different flow regimes.

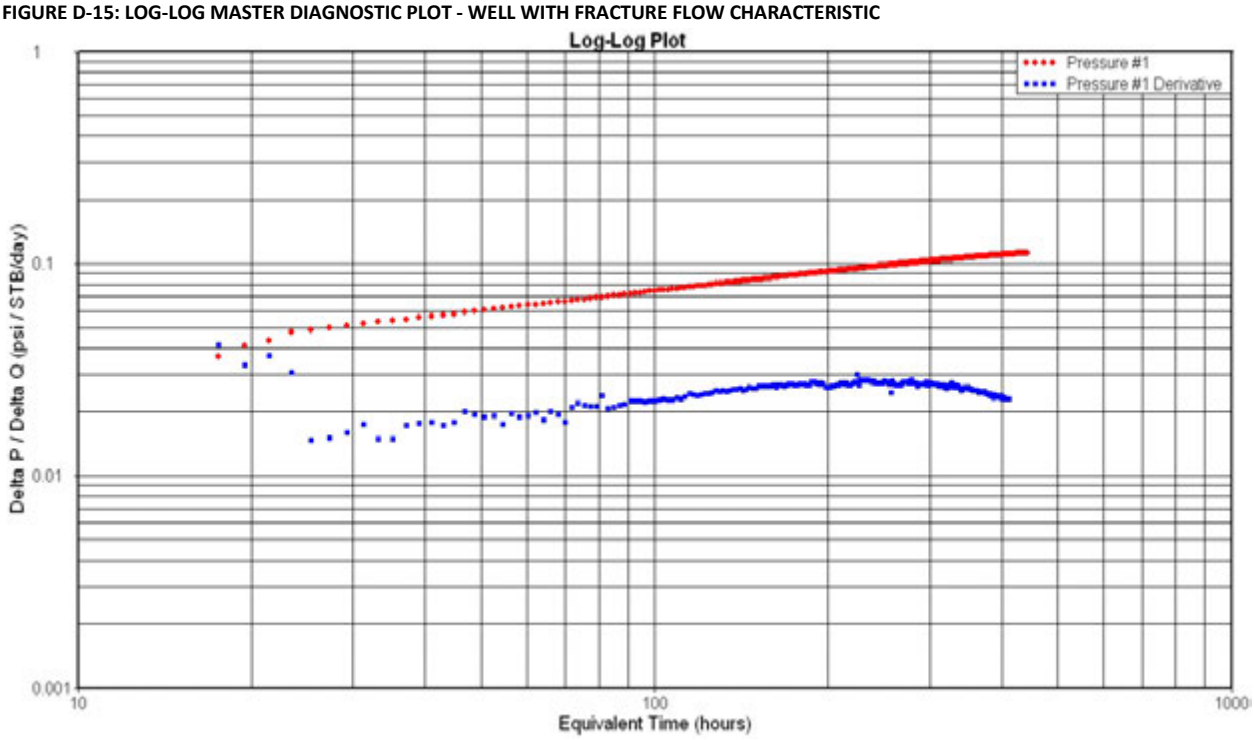
By identifying the flow regimes through a "mathematical picture" on the log-log plot, one can match reservoir model solutions to the test response to characterize the reservoir. The solutions to the reservoir flow models are plotted in the same log-log format, so finding the correct reservoir model becomes a picture matching process between the plotted test data and known reservoir responses.

FIGURE D-14: LOG-LOG MASTER DIAGNOSTIC PLOT OF A FALLOFF TEST



- Log-log diagnostic plot (Figures Figure D-14 and Figure D-15)
    - Logarithmic y-axis:
        - Pressure change, ΔP
            - Subtract the final measured pressure at the end of injection period from each pressure value during the falloff period
            - ΔP increases as pressure declines during the falloff test
            - ΔP divided by ΔQ if rate history is accounted for
        - Pressure derivative, P'
            - Running slope calculated from a semilog plot of falloff pressure versus elapsed test time
    - Logarithmic x-axis:
        - Elapsed test time, Δt, starting from when well is shut-in
        - Time function is modified if the injection rate varied significantly prior to the falloff

FIGURE D-15: LOG-LOG MASTER DIAGNOSTIC PLOT - WELL WITH FRACTURE FLOW CHARACTERISTIC



- Purpose
    - Final falloff pressure provides a static formation pressure measurement
    - Arranges test data in reservoir model format or mathematical "picture"
    - Derivative curve provides a "magnified" look at reservoir transient responses
        - Enhances identification of various flow regimes
        - Couples the log-log and semilog plot

            - Derivative curve is the running slope of the semilog plot
    - Provides reservoir characteristics
        - Identifies flow regimes
            - Derivative flattens during radial flow (See Figure D-14)
        - Identifies reservoir boundaries, if located near the well
    - Measures the transmissibility of the injection zone or reservoir pathway
        - Transmissibility is the formation's ability to transmit pressure
        - Directly relates to the amount and lateral extent of pore pressure buildup
    - Indicates well completion condition
        - Spacing between the pressure and pressure derivative curves
        - Dimensionless wellbore skin factor describes the well completion condition
            - Negative skin: Enhanced completion
            - Positive skin: Damaged completion
            - Fractured wells exhibit very negative skin factors (-5 to -6)
- Challenges
    - Planning of test to obtain good quality data
    - Quality of recording devices to reduce data scatter
    - Ensuring duration of test is sufficient to see beyond wellbore effects and identify reservoir characteristics
    - Special pressure transient software needed to analyze test
    - Handling of wastewater for duration of the test
- Possible red flags
    - Non-radial flow behavior may suggest pressure is not dissipating radially from well
    - Less permeable reservoirs may require longer test times
    - Unanalyzable test—planning or data collection issues

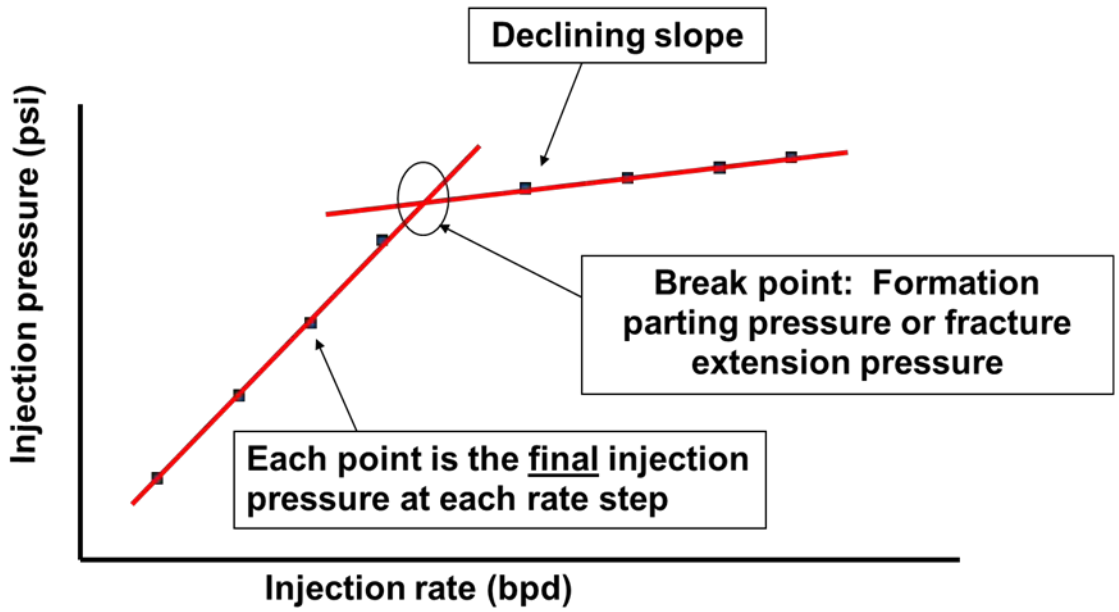
Step Rate Tests

Whereas falloff tests involve shutting in of the disposal well, a step rate test is conducted during operation of the well. Step rate test data can be analyzed either as a composite data set or through individual rate step analyses. Analysis of the composite approach involves a linear plot, while injectivity analysis of individual rate steps involves a more complex log-log plot analysis of each rate step. If both methods are performed, the results can be compared for agreement. The injectivity analysis is similar to the falloff test analysis, except that pressures increase during each rate step instead of decreasing as in a falloff test. However, the limited duration of each rate step results in a shallower look into the reservoir. The goal of both analyses is to determine the reservoir formation parting (fracture) pressure.

Linear Plot

- Linear plot of injection pressure versus injection rate (Figure D-16)
  - y-axis: Final injection pressure of each rate step
    - Bottomhole pressure
  - x-axis: Constant injection rate of each rate step

FIGURE D-16: STEP RATE TEST LINEAR PLOT



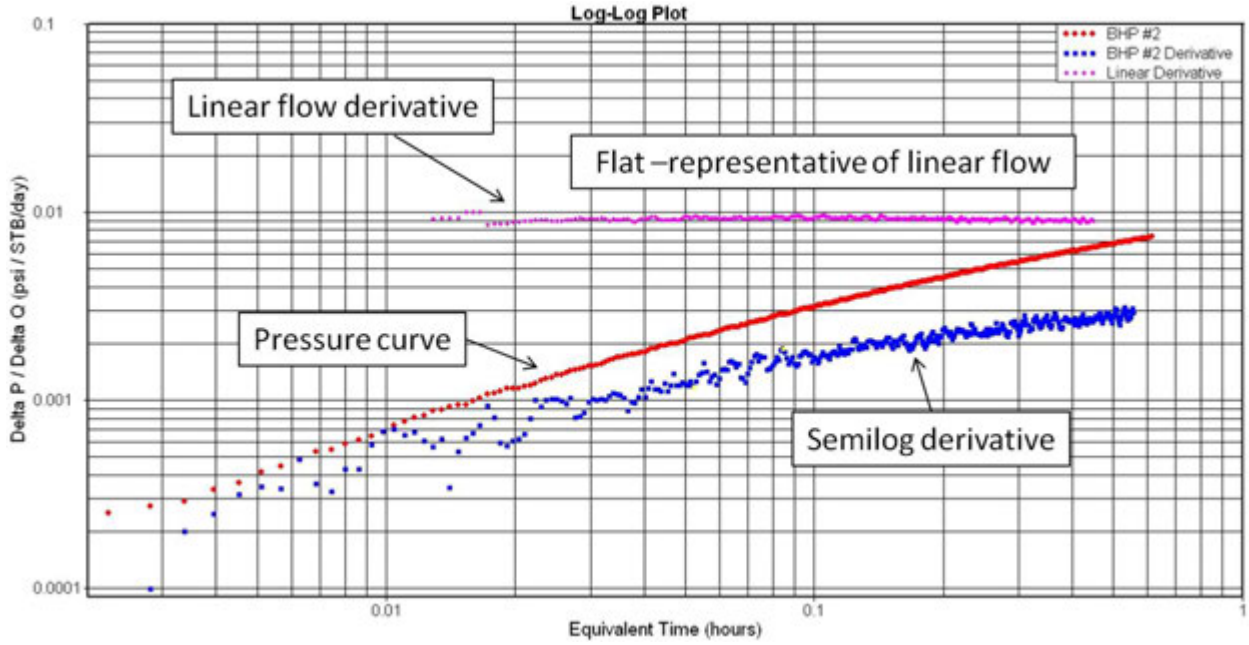
- Purpose
  - Identify formation parting pressure for use in determining maximum allowable operating pressure for disposal well
    - Review data for slope changes by drawing straight line(s) through data points
      - Negative slope break suggests enhanced injectivity or fracturing
      - No slope break
        - Fracture pressure not observed during test
        - Start pressure exceeded fracture pressure
  - Confirm well is operating below the fracture pressure gradient
- Challenges:
  - Surface pressure measurements may provide misleading results
    - Friction effects can mask the slope break
  - Conversion of surface pressures to bottomhole pressure
    - Must account for friction pressure

        - Friction calculation often in error for wells with high injection rates through smaller diameter tubing
    - No break may be observed if disposal well is fractured prior to the first rate step
        - Starting injection rate too high
    - A sufficient number of rate steps must be included in the test to establish straight lines on the linear plot
    - Stabilized pressures are not reached during each rate step
    - Constant injection rates are not maintained during each rate step
        - Test typically requires a pump truck
        - Access to additional fluid volumes for continuous injection
    - Use of continuous pressure and rate recording data throughout the test
        - Allows confirmation of pressure stabilization during each rate step
        - Allows each rate step to be analyzed as an injectivity test

<u>Injectivity Plot</u>

- Log-log injectivity plots of each rate step (Figure D-17)
    - Logarithmic y-axis:
        - Pressure change, ΔP
            - Subtract the pressures measured during injection period of each rate step from the final pressure from the preceding rate step or shut-in pressure for analysis of the first rate step
        - Pressure derivative, P’
            - Running slope of a semilog plot of test data
    - Logarithmic x-axis:
        - Superposition time function to account for changing injection rates during the test

FIGURE D-17: INDIVIDUAL RATE STEP LOG-LOG INJECTIVITY PLOT



- Purpose
  - Identifies flow regime during each rate step
    - Review each step for fracture signature or fracture extension based on fracture half-length
    - Fracture signature suggests formation parting pressure has been exceeded
- Challenges
  - Conversion of surface pressures to BHP required for analysis
    - Must account for friction pressure
    - Requires continuously recorded downloadable electronic data
  - Data can be "noisier" since injection is occurring and passing by the pressure gauge
  - Requires pressure transient software for analysis

How Can the Operational Data and Pressure Transient Test Analyses be Used?

Pressure change in the reservoir can induce seismicity in certain geologic settings. The petroleum engineering approaches described in this appendix may be useful for linking the pressure behavior of the injection well to seismicity. They may also help evaluate area geology and assessment of whether a reservoir is appropriate for a disposal zone. Pressure transient testing identifies flow behavior which indicates how the reservoir pathway pressure increases are distributed away from the disposal well and, in the case of a falloff, measures static pressure for assessing reservoir pressure buildup. For example, pressure increases from a disposal well

exhibiting a fracture or linear flow characteristic may extend directionally over greater distances from the well than would be expected for radial flow.

One aspect of assessing induced seismicity concerns the distance pressure buildup can be transmitted in the disposal reservoir. Two aseismic examples of large distance pressure influence are provided in APPENDIX I: . One example highlights preferential pressure distribution over great distances in a formation suspected of containing a geologic anomaly, and the second example illustrates the cumulative pressure buildup from multiple disposal wells injecting into the same formation.

For disposal wells identified as injecting into linear or fractured flow regimes, expanding the area reviewed may be useful for describing potential reservoir behavior. Typical pressure buildup calculations are based on the assumption that injection occurs into a radially homogeneous, infinite-acting reservoir. Naturally fractured reservoirs generally do not meet these assumptions. Therefore, pressure buildup distribution from a disposal well injecting into a fractured formation may require a more complex evaluation than an analysis for wells injecting into a formation exhibiting radial flow characteristics. In a homogeneous reservoir, the pressure dissipates equally in all directions away from the wellbore; however, the cumulative pressure effects from multiple disposal wells injecting into the same formation may enlarge the area of pressure influence. Though the radial flow equations are applicable, modifications may be necessary to account for multiple pressure sources.

Analysis of the operating data coupled with any available pressure transient tests such as falloff and step rate tests for a disposal well may provide critical details, both geologically and hydraulically, about the nature and conditions of the injection reservoir. An attempt should be made to correlate anomalous test results to area seismic events to determine whether additional data gathering, monitoring or testing is warranted. Since operating data are readily available and require no additional monitoring, the petroleum engineering approach for analysis of such data provides an established technical methodology that may correlate existing well data to seismic events in the area.

HOW DID THE WG PERFORM THE CASE STUDY PETROLEUM ENGINEERING EVALUATIONS?

The detailed assessment for each case study is included in the respective case study appendix. While many of the methods used were highlighted during the preceding discussions, the software used and tasks performed on the case study examples are outlined below. The software listed represents what was available to the WG, but other options are available.

- Software requirements

    - Microsoft Excel® was used for the evaluation of operational data
        - Required assumptions to generate some parameters or functions used
    - PanSystem® software was used to analyze pressure transient data
        - Other pressure transient test software could be used
- Tasks performed for all case study areas
    - Obtained injection pressure, rate and time data for wells within the areas
    - Operational analysis plots generated:
        - Overview plot
        - Operating gradient plot
        - Hall integral plot with derivative
        - Tandem plot
            - Relates cumulative earthquakes to Hall integral
    - Pressure transient test (falloff and step rate) analysis plots generated when data were available:
        - Cartesian overview plot
        - Log-log plot
        - Type curve match where applicable
        - Step rate test linear plot

Glossary of Acronyms and Terms

Acronyms

BHP Bottomhole (static) Pressure (psia)

BPD Barrels per day

BPM Barrels per minute

Cp Centipoise, a measure of viscosity

C_t Compressibility, total (1/psi)

Ei Exponential integral

Gpm Gallons per minute

KB Kelly Bushing (ft)

K Permeability (md or millidarcies)

Kh Permeability thickness (md-ft)

P_{init} Initial pressure (psia)

P_R Pressure, reservoir or formation static (psia)

Φ Porosity

Psia pounds per square inch, absolute

P_{wf} Pressure, well bottomhole flowing (psia)

Q Injection rate (BPD)

r_w Wellbore radius (inches)

STB Stock Tank Barrels, i.e. measured at surface temperature and pressure

TVD True Vertical Depth (ft)

μ Fluid viscosity (cp)

x_f Fracture half-length (ft)

TERMS

Falloff test is a pressure transient test conducted by shutting an injection well in and observing the pressure decline at the well over a period of time.

Formation parting pressure is the pressure required to extend a created fracture or preexisting, natural fracture. It is also referred to as the fracture extension pressure. This pressure is less than the pressure required to initiate a fracture which is referred to a fracture or breakdown pressure.

Fracture gradient is the minimum pressure required to induce fractures or fracture extension in a rock at a given depth.

Fracture half-length is the radial distance from the wellbore to the outer tip of a fracture penetrated by the well or propagated from the well by hydraulic fracturing. (Schlumberger)

Fracture pressure, aka breakdown pressure, is the pressure above which injection of fluids will cause the subsurface rock formation to fracture. Typically 65-85% of overburden pressure, and about 0.71 psi per foot of overburden depth. (Schlumberger, 2014 and Hayes, 2014)

Offset well is an existing well in proximity to the well of interest, which may provide analogous information.

Kelly bushing (KB), aka rotary Kelly bushing, is a common wellhead reference point for measuring the depth of a well. It is an adapter that connects the rotary table to the Kelly—a long steel bar used to transmit rotation to the drill string.

Radial diffusivity equation is the basic equation used in wellbore pressure analysis. Solution typically used: $P_r = P_{init} + (162.6 * Q * \mu * B/(k * h)) * \log ((k * t) / (70.4 * \Phi * \mu * C_t * r * r))$

Step rate test consists of a series of increasing injection rates as a series of rate steps and estimates the pressure necessary to fracture the formation.

Static pressure, for this report, is the bottomhole pressure in the pore volume around the injection well measured in the wellbore at the end of a shut -in period that reaches stabilized conditions.

Transmissibility (kh/μ) is the reservoir permeability times the net thickness divided by the fluid viscosity. It is an overall measure of a reservoir's capability to accept fluid injection.

True vertical depth (TVD) is the vertical distance from the wellbore reference point to a measured depth point, regardless of offset lateral distance. Hydrostatic head is measured based on the true vertical height of the fluid column.

Wellbore skin shown by well testing is a zone of reduced or enhanced permeability around a wellbore, often explained by formation damage during injection operations and mud-filtrate invasion during drilling or perforating, or by well stimulation. A positive skin value indicates some damage or influences that are impairing well productivity. A negative skin value indicates enhanced productivity, typically resulting from stimulation. (Schlumberger)

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APPENDIX E: NORTH TEXAS CASE STUDY AREAS: DFW AND CLEBURNE

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All four case studies were considered in the development of the decision model. Consequently, the Injection-Induced Seismicity Working Group (WG) elected to apply the decision model framework to the case study events. Following the decision model framework, the wells in this case study fall under both the new and existing well categories. This case study covers a broad section of the Fort Worth Basin, with two focus areas. In both areas, increased earthquake frequency and magnitude following the start of disposal operations raised concern. Future disposal wells may fall in the category of new wells in an existing area of seismic concern, depending on the level of seismicity selected as a cutoff.

North Texas Case Study Background

In late 2008, a series of small earthquakes occurred in north Texas near Dallas-Fort Worth (DFW) International Airport, followed by a separate group of small earthquakes starting in mid-2009 around Cleburne. Both areas are within the active Barnett shale play (Figure E-1). Deployment of temporary seismic arrays helped identify the source of the earthquakes.

To aid understanding of the various findings, this appendix describes the geologic setting, existing oil and gas activity, and seismic history prior to providing details on the two separate areas and nearby disposal operations.

Geologic Setting

The DFW and Cleburne focus areas are located within the Fort Worth Basin. The generalized east-west cross-section (Figure E-2) shows the relationship of the formations bounded on the east by the Ouachita thrust fault against basement rocks. The generalized north-south cross-section in Figure E-3 shows later Pennsylvanian age normal faulting (Bruner and Smosna, 2011). A third faulting episode appears in the basin, resulting from collapsed chimney structures above Ellenburger karst sinkholes and caverns (Bruner and Smosna, 2011; McDonnell, 2007;

Montgomery et al., 2005; Steward, 2011; Sullivan et al., 2006), illustrated in Figure E-4 (Steward, 2011). The case study Class II disposal wells are completed in the Ellenburger formation.

The Barnett Shale lies below the Mississippian-Pennsylvanian unconformity, and unconformably over Ordovician carbonates (Viola, Simpson and Ellenburger formations). As shown in Figures E-2 and E-3, the Barnett shale can lie directly on the Ellenburger. Therefore, there may be little or no confining strata between the Barnett and the underlying disposal zone.

During a meeting between EPA Region 6 and an area operator, the operator presented geologic data gathered in portions of the Fort Worth Basin that indicated there are no obvious Ellenburger karst features in the DFW airport area; however, the area around Cleburne showed significant karst features. The presentation displayed a major normal fault with approximately 600 feet of displacement, down to the east-southeast, in the DFW area. This same fault is also shown in literature (Figure E-5), and is located about a mile (1.6 km) west of the disposal well, DFW C1DE (Ficker, 2012; Frohlich et al., 2011).

Oil and Gas Activity

The Barnett shale production discovery took place in 1981 in Newark East field, in Wise County. Since 2002, most Barnett shale wells have been horizontally drilled with 1,000- to 3,500 foot lateral legs (Martineau, 2007). In Newark East, the top Barnett shale depth ranges from 6,900 to 7,500 feet, with a thickness varying from 200 to over 700 feet near the Muenster Arch in the northeast (Montgomery et al., 2005).

History of Seismicity

Prior to October 2008, no earthquakes were reported in any of the six seismicity databases, [USGS Advanced National Seismic System (ANSS), Eastern, Central & Mountain States NEIC Earthquake database (SRA), Central and Eastern United States CERI Earthquake database (NCEER), Significant U.S. quakes, NEIC Earthquake database (USHIS), Center for Earthquake Research and Information (CERI) and Preliminary Determination Earthquake, NEIC Earthquake database (PDE)], within 40 miles (64 km) of the DFW International Airport or the Cleburne area.

However, several small (M1.7 to M3.3) earthquakes occurred in the central part of the Dallas - Fort Worth metroplex near DFW International Airport starting on October 31, 2008. The case study wells in the DFW area began operations in June 2007 and March 2008. Seismic activity (M2.0 to M3.3) near the town of Cleburne started on June 2, 2009. The ten case study wells in the Cleburne area began operations between December 2005 and May 2008. Both focus areas are located in north central Texas and the eastern portion of the Barnett shale play (Figure E-1).

North Texas Information Collected

Data for wells in the DFW and Cleburne focus areas were downloaded from the Texas Railroad Commission (RRC) website. Supplemental geosciences information was obtained through the deployment of additional seismometers. Operational monitoring reports provided monthly injection rates and wellhead pressures. Details for each focus area are included in the relevant Information Collected sections below.

Permitting and well documents provided details concerning completion depths, construction information and permit conditions for the case study wells. Annual operation reports provided monthly injection volumes and average and maximum wellhead pressures. Well pressures and injection volumes available as of December 1, 2013, were obtained from the RRC disposal well database.

Location and operating status of each Class II disposal wells in the focus areas were updated from the RRC website through mid-August 2013. Locations of seismic events through September 30, 2013, were downloaded from the seismic event databases discussed for each of the focus areas.

Operational Details

For both the DFW airport and Cleburne study areas, the individual well surface pressures were converted to approximate bottomhole pressure (BHP) at tubing seat depths. For this conversion, a fluid specific gravity of 1.05 (roughly equivalent to 45,000 parts per million chlorides) was assumed. Tubing dimensions, length and inside diameter, were taken from or estimated from permit documentation. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor C of 100 for steel tubing was used. BHPs were calculated by adding the surface pressure and the pressure of the hydrostatic column of fluid and subtracting the calculated friction pressure loss. Operating data-related plots were prepared for selected wells within the case study areas consisting of a seismicity timeline, an operational overview data plot, operating pressure gradient plot, and a tandem plot of Hall integral with derivative and seismic events. The tandem plot shows both the Hall integral and cumulative area earthquake events against a common scale of cumulative disposal volume.

Focused Site Assessment for DFW International Airport Area

Earthquake activity near DFW International Airport occurred between October 31, 2008, and May 16, 2009, with episodic recurrence. Based on earthquake activity and the regional seismometer network capabilities, an arbitrary 5 mile (8 km) radius was selected to define the focus area around suspected wells. The selected composite focus area is shown in Figure E-6 and includes two disposal wells located within the airport property boundary. The available seismic

databases listed no earthquakes around the northern well. However, as shown in Figure E-7, some of the relocated events are just outside the focused radius of the northern well.

Information Collected

Disposal Well in DFW International Airport Case Study Area

Data were gathered from the permit application and operational history for the two focus wells in Tables Table E-1 and Table E-2.

TABLE E-1: DFW FOCUS WELL INJECTION PERMIT CONDITIONS AND COMPLETION DATA

	Injection Permit Conditions					Completion Data (feet Measured Depth)				
Disposal Wells (SWD)	UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation	Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
DFW C1DE	98402	No	5,023	25,000	Ellenburger, open-hole	10,252’	13,729’	13,729’	7” to 10,253’	3 ½” to 10,181’
DFW North A1DM	97642	No	4,400*	25,000	Ellenburger, open-hole	8,802’	13,165’	13,190’	7” to 8,800’; 4 ½” liner 13,166’	4 ½” to 8,800’

*** AMENDED FROM 4,575**

DEPTHS ARE MEASURED DEPTHS IN FEET, NOT TVD

TABLE E-2: DFW FOCUS WELL OPERATIONS

Disposal Wells (SWD)	Operations			Comments
	Initial Disposal	Final Disposal	Cancelled Disposal Permit	
DFW C1DE	Sept. 2008	Aug. 2009	Sept. 25, 2009	Temporarily Abandoned
DFW North A1DM	Nov. 2007			Disposal continues; 4.5” liner run from 8722-13166’ on Oct. 22, 2009

ADDITIONAL GEOSCIENCES INFORMATION

Additional seismometers (Figures E-6 and E-8) installed after seismicity began included a temporary network operated by Southern Methodist University (SMU) and two permanent stations installed by an area operator. The temporary network was deployed between November 2008 and early January 2009 (Frohlich et al., 2011). The two new permanent stations were added October 2009 and April 2010 (Janská and Eisner, 2012).

The DFW airport area earthquakes recorded in the ANSS, Comprehensive catalog (ComCat) and National Earthquake Information Center, U.S. Geological Survey (NEIC) catalogs, supplemented with published SMU temporary array events (Frohlich et al., 2011) within the focus radius of the disposal wells, are summarized in Table E-3 below and on a timeline illustrated in Figure E-9. Note that only events that included a magnitude value were incorporated into this report. Earthquakes from the other seismometers were not included in the table below as the specific data were not published.

TABLE E-3: DFW AIRPORT AREA SEISMICITY THROUGH SEPTEMBER 30, 2013

Year	Starting Event	Number of Events	Magnitude			Ending Event
			Min.	Avg.	Max.	
2008	10/31/2008	18	1.7	2.4	3.0	12/1/2008
2009	5/16/2009	3	2.6	3.0	3.3	5/16/2009
2010	11/23/2010	2	2.4	2.5	2.5	12/13/2010
2011	8/1/2011	2	2.2	2.4	2.6	8/7/2011
2012	9/30/2012	1		3.4		9/30/2012
2013	1/23/2013	1		3.0		1/23/2013

THE 2013 EVENT 10 MILES (16.1 KM) DEEP AND ONE 2009 EVENT 5/16/09 M3.3 EVENT 5.4 MILES (8.7 KM) DEEP WERE CONSIDERABLY DEEPER THAN ALL THE OTHER EVENTS, WHICH WERE REPORTED AT THE DEFAULT 5 KM VALUE. SMU'S RECALCULATED DEPTHS WERE BETWEEN 2.7 AND 2.8 MILES (4.34 AND 4.46 KM) FOR THE 2008 EVENTS.

The seismicity in Figure E-7 (Janská and Eisner, 2012) suggests a clearly defined seismically active fault to the west and south of the disposal well location, DFW C1DE, along with a scattered seismicity area to the northeast. Published reports agree that the 2008 through 2009 seismicity occurred along the north-south trending fault to the west of the DFW C1DE well. The reports disagree on the actual focus depth and probable cause (Janská and Eisner, 2012; Reiter et al., 2012; Eisner, 2011; Frohlich et al., 2011).

Expansion of the arbitrary focus area from 5 to 6 miles for the DFW North A1DM well allowed for the inclusion of the northeast cluster of earthquakes identified inside the airport ring, (Figure E-7). Table E-4 includes only two events above M2.5 but includes all the events within the 6 mile radius picked up by the WMOK station (Figure 4 of Janská and Eisner, 2012).

TABLE E-4: ADDITIONAL RELOCATED SEISMICITY (JANSKÁ AND EISNER, 2012)

Event at WMOK	Number of Events	Maximum Magnitude
5/2/2010	3	1.66
5/26/2010	17	2.17
6/26/2010	7	1.47
11/1/2010	7	2.26
11/23/2010	7	2.15
8/7/2011	6	2.60
1/23/2013	1	3.00

PETROLEUM ENGINEERING REVIEW

OPERATIONAL ANALYSIS

Only operational data were available so no pressure transient test analyses were conducted in the DFW airport focus wells. Figures E-10 through E-13 provide operational data overview plots and calculated operational pressure gradient plots for DFW C1DE and DFW North A1DM. Figure E-14 is a tandem plot of the Hall integral with derivative and seismic events for C1DE, and Figure E-15 is the Hall integral and derivative plot for A1DM and seismic events.

Table E-5 summarizes the assumed reservoir pressure value used in the Hall integral calculation for the Hall plot.

TABLE E-5: DFW AIRPORT FOCUS AREA HALL INTEGRAL ASSUMED INITIAL PRESSURE VALUE

Well	Hall Assumed Average Pressure (psi)
DFW C1DE	4,545
DFW North A1DM	3,900

DFW C1DE

- Operational data overview plot (Figure E-10)
    - Well was temporarily abandoned in August 2009
- Operating pressure gradient plot (Figure E-12)
- Tandem plot of Hall integral and derivative plot and seismic events (Figure E-14)
    - Showed no clear correlation between the Hall integral with derivative response and cumulative earthquake trend

DFW North A1DM

- Operational data overview plot (Figure E-11)

    - Injection volume declined during last half of the well operational history while injection pressure trend was generally unchanged
- Operating pressure gradient plot (Figure E-13)
- Hall integral and derivative plot (Figure E-15)
    - Hall integral with derivative responses showed multiple pronounced upswings
        - Upswing may represent a reservoir boundary effect
    - No seismic event locations available for correlation purposes (see next section)

Summary of Engineering Analysis

Operational data were reviewed for two wells in the DFW area, DFW C1DE and DFW North A1DM. The initial engineering analysis showed no clear correspondence between well behavior and seismic events for either well with an arbitrary 5 mile focus area. The southern well (DFW C1DE) operated only for 1 year, resulting in limited data for analysis. Expanding the northern well (DFW North A1DM) focus area to include the area covered by a 6 mile (10 km) radius allows consideration of later reported seismic events, (Janská and Eisner, 2012; Eisner, 2011). For those events, a cycle of increasingly difficult injection preceded the seismic events (see Figure E-15).

Actions Taken by UIC Regulatory Agency in DFW Airport Study Area

Following the 2008 seismic events, the RRC worked with the operator of the disposal well, DFW C1DE, nearest to the seismicity. The operator voluntarily shut the well in. The RRC reviewed its permit actions for other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found from these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, along with researchers at the Bureau of Economic Geology, SMU and Texas A&M University, and continues to monitor developments and research related to injection-induced seismicity.

DFW Area Multidisciplinary Integration of Findings

Published reports agree that the 2008–2009 seismicity occurred along the fault west and north of the DFW C1DE well (Figure E-6). This well was voluntarily shut-in during August 2009. The May 2010 cluster appears to be further northeast along the same fault identified by Ewing (1990) (Figure E-7). The reports disagree on the actual focus depth and probable cause (Janská and Eisner, 2012; Eisner, 2011; Frohlich et al, 2011).

The engineering analysis showed no correspondence between well behavior and seismic events for either well with an arbitrary 5 mile focus area. However, the closest well, DFW C1DE, started disposal operations in September 2008, and the first seismicity occurred in late October. The well only injected for a year prior to voluntary shut-in. Expanding the northern well (DFW North

A1DM) focus area to include an area defined by a 6 mile (10 km) radius allowed consideration of later reported seismic events, (Janská and Eisner, 2012; Eisner, 2011). For those events, there was a slight correspondence between the seismicity and decreased injectivity.

Focused Site Assessment For Cleburne Area

Following the Cleburne area initial seismic events on June 2, 2009, the earthquake activity areally expanded over time, as shown in Figure E-16. There are a number of active disposal wells in the area injecting into the Ellenburger below the Barnett shale. Ten focus wells were selected based on their proximity to the initial seismic events. The focus study boundary, shown in Figure E-16, was based on earthquake activity and the regional seismometer network capabilities and merging of an arbitrary 5 mile (8 km) radius around each of the wells. The seismic events labeled '2011-J-A' in Figure E-16 are discussed in Frohlich (2011) but are located outside the focused area for this report.

Of the 10 case study wells in the Cleburne study area, some of the wells were in close proximity to each other. Offset disposal should be considered when evaluating disposal well behavior.

Information Collected

Disposal Wells in Cleburne Case Study Area

Data were gathered from the permit application and operational history for all the focus wells in Tables Table E-6 andTable E-7.

TABLE E-6: CLEBURNE NORTH TEXAS FOCUS AREA WELLS PERMIT AND COMPLETION CONDITIONS

	Injection Permit Conditions					Completion Data (feet Measured Depth)				
Disposal Wells (SWD)	UIC Permit	Com-mercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation	Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
Hanna 1	96321	Yes	3,800	20,000	Ellenburger	8,006	10,700	10,700	7" to 8,006'	3 ½" to 7,920'
Johnson Salty 3	96488	Yes	3,500	30,000	Ellenburger	7,850	10,000	12,000	7" at 9,799'	4" at 7,100' Replaced w/ 4½" at 7,750' in Mar. 2011
Rose 1	98425	Yes	2,500	30,000	Ellenburger	9,104	11,250	11,428	7" at 11,428'	4½" at 8,927'
Vortex 1	95462	Yes	4,300	37,000	Ellenburger	10,430 11,094'	10,644 11,235'	11,250	7" at 11,250'	4½" at 10,376'
S Mann 1	94931	Yes	3,708	20,000	Ellenburger	7,627	9,071	9,071	7" at 7,627'	3 ½" at 7,425'
Sparks Drive 1	93369	Yes	2,900	15,000	Ellenburger; open-hole	7,509	9,134	9,134	5 ½" at 7,509'	3 ½" at 7,421'
Johnson County 1	95581	No	3,800	25,000	Ellenburger; open-hole	7,995	10,821	11,213	7" at 7,994'	4 ½" at 7,981'
South Cleburne 1	94930	yes-TA	3,650	20,000	Ellenburger	10,422	10,755	10,952	7" at 10,903'	4½" at 10,349'
Cleburne Yard 1	97113	Yes	2,300	15,000	Ellenburger	7,650	11,500	10,128	7" at 7,850'	4 ½" at 7,765'
Johnson Salty 2	96487	Yes	3,500	30,000	Ellenburger	7,210	10,000	10,000	7" at 9,808'	4" at 6,950' Replaced w/ 4½" at 7,080' in Mar. 2011

TABLE E-7: CLEBURNE NORTH TEXAS FOCUS AREA WELLS OPERATING STATUS

Disposal Wells (SWD)	Operations			Comments
	Initial Disposal	Final Disposal	Plugged and Abandoned	
Hanna 1	Apr. 2007			Operating
Johnson Salty 3	Jan. 2007			Operating
Rose 1	May 2008			Operating
Vortex 1	Dec. 2006			Operating
S Mann 1	Oct. 2006			Operating
Sparks Drive 1	Dec. 2005			Operating
Johnson County 1	Apr. 2007			Operating
South Cleburne 1	Oct. 2006	Jul. 2009		Temporarily abandoned
Cleburne Yard 1	Aug. 2007			Operating
Johnson Salty 2	Jan. 2007			Operating

Additional Geosciences Information

The Cleburne area earthquakes were downloaded from the ANSS, ComCat and NEIC catalogs. Additional seismometers as shown in Figure E-17 were deployed between June 2009 and June 2010 by SMU (Howe-Justinic et al., 2013).

A summary of the Cleburne area earthquakes is included in Table E-8, and in a timeline in Figure E-18.

TABLE E-8: CLEBURNE FOCUS AREA SEISMICITY THROUGH SEPTEMBER 30, 2013

Year	Starting Event	Number of Events	Magnitude			Ending Event
			Min.	Avg.	Max.	
2009	6/2/2009	9	2.0	2.4	2.8	10/1/2009
2010	11/8/2010	2	2.1	2.3	2.5	11/12/2010
2011	6/7/2011	1		2.2		6/7/2011
2012	1/18/2012	18	2.1	2.7	3.6	7/28/2012
2013		0				

Since 2009, Cleburne area events have been continuously reprocessed and relocated with significant changes to event locations. For example, one event was relocated a distance of 7 km on the surface and 1 km in depth. The published supplemental data from the additional seismometers that provided the relocations were not available in time to be incorporated into this report, but their locations are shown with a + symbol on the map (Figure E-17). The relocation report (Howe-Justinic et al., 2013) identified a total of 54 events picked up by the temporary array in a well-defined fault approximately 2 km long oriented in a north-northeast direction, as shown in Figure E-17. The relocation places the fault hypocenters within the depth range of permitted injection by the closest two wells, (Cleburne Yard and South Cleburne). The authors noted, "Although the orientation of the fault estimated by the locations departs slightly from the mapped faults in the region … the departure is small and may reflect local variations in strike within the region."

Operational Data

The Sparks Drive SWD 1 well is dually permitted as a Class II commercial with the RRC and as a Class I disposal well with the Texas Commission on Environmental Quality (TCEQ). Class I wells are required to conduct annual falloff tests. EPA acquired the 2005, 2006 and 2008–2011 annual falloff pressure transient tests for Sparks Drive SWD 1. Analyses of these pressure transient tests for Sparks Drive SWD 1 are included in this case study. No pressure transient tests were available for the other wells.

Petroleum Engineering Review

Operational Analysis

Operational data were reviewed and analyzed for all 10 wells. The analysis plot for each well is included in the following list of figures:

- Operational data overview plots: Figures E-19 through E-28
- Operating pressure gradient plots: Figures E-29 through E-38
- Tandem plot of Hall integral with derivative and cumulative earthquake events: Figures E-39 through E-48

Table E-9 summarizes the assumed reservoir pressure value used in the Hall integral calculation for each Hall plot. Hydrostatic pressures were used to calculate a reservoir pressure for all the wells.

TABLE E-9: CLEBURNE AREA HALL INTEGRAL ASSUMED INITIAL PRESSURE AND ASSOCIATE FIGURES

Disposal Wells (SWD)	Figures E-	Hall Plot Assumed Initial Pressure (psia)
Hanna 1	19, 29 and 39	3,432
Johnson Salty 3	20, 30 and 40	3,160
Rose 1	21, 31 and 41	4,059
Vortex 1	22, 32 and 42	3,910
S. Mann 1	23, 33 and 43	3,375
Sparks Drive 1	24, 34 and 44	3,375
Johnson County 1	25, 35 and 45	3,630
South Cleburne 1	26, 36 and 36	4,705
Cleburne Yard 1	27, 37 and 47	3,530
Johnson Salty 2	28, 38 and 48	3,160

The operating pressure data analysis completed for each well is summarized below.

- Operational data overview plots (Figures E-19 through E-28)
  - Injection volume declined while injection pressure trend was generally unchanged (Figures E-19, E-23, and E-25)
  - South Cleburne was temporarily abandoned in August 2009
- Operating pressure gradient plots (Figures E-29 through E-38)
  - All wells had operating pressure gradients below 0.75 psi/ft
- Tandem plots of Hall integral with derivative and seismic events (Figures E-39 through E-48):
  - Hanna (Figure 39)

    - Multiple periods of enhanced injectivity followed by earthquake events and positive upswing in Hall integral and derivative responses
    - Hall integral response similar to offset Johnson Salty 3 disposal well
- Johnson Salty 3 (Figure E-40)
    - Multiple positive upswings in Hall integral and derivative responses, with only one upswing corresponding with two earthquake events
    - Hall integral response similar to offset Hanna disposal well
- Rose (Figure E-41)
    - Enhanced injectivity followed by a positive upswing in Hall integral and derivative responses and earthquake events
    - Hall integral response similar to offset Vortex disposal well
- Vortex (Figure E-42)
    - Multiple positive upswings in Hall integral and derivative followed by earthquake events, with the last upswing more pronounced and corresponding to earthquake events
    - Hall integral response similar to offset Rose disposal well
    - Cumulative injection volume only through November 2012, as more recent operational data were unavailable as of December 2013
- S. Mann (Figure E-43)
    - Initial enhanced injectivity followed by positive upswings in Hall integral and derivative responses, with earthquake events occurring around the beginning of the second upswing
    - Similar response to offset Sparks Drive disposal well
- Sparks Drive (Figure E-44)
    - Initial enhanced injectivity followed by positive upswings in Hall integral and derivative responses, with earthquake events occurring around the beginning of the second upswing
    - Similar response to offset Mann disposal well
- Johnson County (Figure E-45)
    - Two positive upswings in Hall integral and derivative followed by earthquake events, with the second upswing more pronounced
- South Cleburne (Figure E-46)
    - Enhanced injectivity during operational period through July 2009
    - Last 4 earthquake events occur in 2012, with no injection occurring in well since July 2009
- Cleburne Yard SWD 1 (Figure E-47)

        - Two positive upswings in Hall integral and derivative followed by enhanced injectivity periods, subsequently followed by a third more pronounced upswing in the Hall integral and derivative
        - Earthquakes correspond to the second and third upswings in the Hall integral and derivative plots
    - Johnson Salty 2 (Figure E-48)
        - Slight positive upswing in Hall integral and derivative corresponding with the two earthquake events in well focus area
        - Second positive upswing in Hall integral and derivative, but no corresponding earthquake events

PRESSURE TRANSIENT ANALYSIS

Annual falloff test data for Sparks SWD 1 were analyzed using PanSystem® well test software. Each test was plotted in a log-log format with the derivative response and then compared against various reservoir type curve models to identify flow regimes and reservoir and completion characteristics present. Data specific to each falloff test is summarized in Table E-10.

A summary of the Sparks Drive SWD 1 pressure transient test plot analyses is shown in Table E-11 and additional discussion on select tests is included below:

- 2005 and 2006 falloff test
    - Overview plot (Figures E- 49 and E-50)
        - 2005 pressure declining measurably (1.33 psi/hr) at the end of the test (E-49)
        - 2006 pressure declining measurably (1.74 psi/hr) at the end of the test (E-50)
    - Log-log plot (Figures E-51 and E-52)
        - 2005 and 2006 plots suggest a highly stimulated completion followed by a pressure derivative decline (Figures E-51 and E-52, respectively)
        - 2006 – linear derivative added indicating linear flow during part of the test (Figure E-52)
    - Type curve match (Figures E-53 through E-55)
        - 2005 infinite conductivity fracture type curve (Figure E-53)
            - Suggests high conductivity fracture
        - 2006 test could be matched using only the early (Figure E-54) or late time (Figure E-55) portions of the tests
            - Overall test did not fit a single type curve model

            - Both early and late responses fit a fracture type curve model with similar fracture half-length dimensions
            - Early response kh result was roughly twice late response kh value
- 2008 falloff test
    - Overview plot (Figure E-56)
        - Pressure declining measurably (1.26 psi/hr) at the end of the test
    - Log-log plot (Figure E-57)
        - Linear flow behavior followed by late time derivative decline
    - Type curve (Figures E-58 and E-59)
        - Radial homogeneous type curve (Figure E-58)
            - Suggests a stimulated completion
        - Infinite conductivity fracture type curve (Figure E-59)
            - Highly conductive fracture with results similar to 2005 and 2006 falloff tests
- 2009 falloff test
    - Overview plot (Figure E-60)
        - Pressure declining measurably (0.82 psi/hr) at the end of the test
    - Log-log plot and dual permeability type curve (Figure E-61)
        - Late time data shows a derivative decline with a negative half slope
            - Possibly indicating spherical flow/layering
        - Late time portion of test fit a two layer model
- 2010 falloff test
    - Overview plot (Figure E-62)
        - Pressure declining measurably (2.45 psi/hr) at the end of the test
    - Log-log plot and type curve matches (Figures E-63 and E-64)
        - Linear flow with late time derivative decline
        - Infinite conductivity fracture type curve (Figure E-63)
            - Highly conductive fracture similar to 2005, 2006 and 2009 falloff tests
        - Dual permeability type match with late time data only (Figure E-64)
            - Late time portion of test fit a two layer model
- 2011 falloff test
    - Overview plot (Figure E-65)
        - Pressure declining measurably (3.38 psi/hr) at the end of the test
    - Log-log plot and type curve match (Figure E-66)
        - Highly stimulated completion
        - Infinite conductivity fracture type curve

- Marginal match with a highly conductive fracture similar to 2005, 2006, 2009 and 2010 tests

TABLE E-10: SPARKS DRIVE SWD 1 (WDW 401) FALLOFF TEST CONDITIONS

Test Date	Injection Time (hrs)	Shut-in Time (hrs)	Gauge Depth (ft KB)	Final Injection Pressure (psia) and Rate (gpm)	Final Shut-in Pressure (psia) and Pressure Decline Rate (psi/hr)
8/29-30/2005	30.12	18.7	7,620	4,189.33/ 156	3,851.12 / 1.33
9/21-22/2006	16	20.5	5,500	3,361.79/ 173	2,921.68/ 1.74
8/25-26/2008	13.17	21.25	7,500	4,227.07/ 215	3,859.42/ 1.26
8/27-28/2009	124.2	21.18	6,334	3,781.70/ 128	3,281/ 0.82
8/4-5/2010	18.5	20	7,620	4,252.49/ 95.5	3,876.98/ 2.45
8/1-2/2011	240	20.2	7,620	4,316.90/ 99	3,973.69/ 3.38

SPARKS DRIVE SWD 1 FALLOFF TESTS SUMMARY

Tests generally indicated a fractured or highly stimulated completion signature, but entire test responses did not fit a simple model. Early time test responses were fitted to type curve models, while the late time portions of the test deviated from the type curve response.

Late time test behaviors indicated pressure support/communication in the form of a declining pressure derivative response. This could reflect communication with a pressure support source, such as another layer and offset disposal well. Two of the late time test responses fit a dual permeability (two layer) type curve model.

Type curve matches were marginal, but all indicated a highly stimulated completion with matches obtained using both homogeneous reservoir and infinite conductivity fracture type curves to match the early portions of several falloffs. As the Ellenburger formation is naturally fractured, this type of response is consistent.

Matches also indicated a moderate transmissibility interval with transmissibilities in the 4,000-15,000 md-ft/cp range. Fracture characteristics from the type curve matches fit an unpropped fracture with fracture wing lengths on the order of 160 to 250 feet long.

The falloffs did not reach static pressure conditions at test end time as all the falloffs displayed noticeable pressure declines at their conclusions.

TABLE E-11: CLEBURNE AREA FALLOFF TEST ANALYSIS SUMMARY

Test	Type Curve Model	kh/u (md-ft/cp)	Skin Factor	x_f (ft)	Comments
2005	Homogeneous	3,633	-5.3	---	
	Infinite Conductivity Fracture	3,287	-5.7	200	
2006	Finite Conductivity Fracture	10,380	-4.5	190	
	Infinite Conductivity Fracture	10,380	-4.5	160	Early time data match
	Infinite Conductivity Fracture	4,325	-5.6	170	Late time data match
2008	Homogeneous	13,107	-5.3		
	Infinite Conductivity Fracture	12,317	-5.4	176	
2009	---	---	---	---	Not quantitatively analyzable
2010	Infinite Conductivity Fracture	2,595	-5.6	175	
2011	Infinite Conductivity Fracture	4,556	-5.5	254	

SUMMARY OF ENGINEERING ANALYSIS

The Sparks Drive injection well, located in the Cleburne area, was the only well included in the Texas case study to have pressure transient tests available, as it was dually permitted as both a Class I and Class II injection well. A total of six annual falloff tests for 2005, 2006 and 2008-2011 were available for review. All six tests showed moderate transmissibity with a linear flow signature, representative of a hydraulic planar fracture and suggesting that the injection pressure was not immediately dispersed radially away from the well, but linearly along the fracture direction. The fracture wing lengths were consistently estimated as over 150 feet in length. Table E-11 provides a quantitative analysis for each of the six falloff tests while Table E-10 summarizes test conditions for each test.

For the 10 Cleburne area wells, operating gradient, Hall integral and derivative plots, and tandem plots were prepared from program-reported operating data. Although average operating gradient data were generally below 0.75 psi/ft for the 10 wells, all wells displayed periods where maximum operating gradients well were above the 0.75 value, which could have led to unintended formation fracturing from disposal operations.

The tandem plots for Hanna and Johnson Salty 3 wells showed similar responses, with upswings in the Hall integral and derivative responses, indicating increasingly difficult injection just prior to and during area seismic events and suggesting a correspondence between the wells' long term hydraulic behavior and earthquakes. The South Mann and Sparks disposal wells displayed similar tandem plot responses with an initial period of enhanced injectivity (possibly fracturing)

following upswings in the Hall integral and derivative responses corresponding to and immediately preceding area seismic events, again suggesting correspondence between a signature of reduced ease of injection and area earthquakes. The Rose and Vortex wells also displayed tandem plot responses similar to those of the other two pairs of Cleburne area disposal wells, with upswings in the Hall integral and derivative responses corresponding to and immediately preceding area seismic events. These six wells were grouped into pairs in accordance with their physical locations in the Cleburne area.

The remaining four Cleburne area disposal wells are summarized individually. The Johnson County disposal well showed two periods of increasingly difficult injection followed by two clusters of seismic events; once again the tandem plot analysis suggested a correspondence between the signature of reduced ease of injection and area earthquakes. The South Cleburne well's tandem plot showed no correspondence between area earthquakes and injection, since injection ceased in 2009 and seismic events near the well occurred after injection ceased. The Cleburne Yard well's tandem plot showed three periods of increasingly difficult injection with clusters of seismic events corresponding to the beginning of the second and third periods. The Johnson Salty 2 showed two periods of increasingly difficult injection on its tandem plot, with the first period corresponding to two earthquake events in the well's area. In general, the Cleburne area disposal wells showed a fairly consistent correspondence between occurrences of increasingly difficult injection and area seismic events, as noted on the tandem plots.

Actions Taken by UIC Regulatory Agency in the North Texas Cleburne Area

Following the 2009 seismic events, the RRC worked with the operator of the nearest disposal well, South Cleburne SWD 1. The operator voluntarily shut the well in, though it did not consider the evidence to be conclusive. The RRC reviewed its permit actions for this well, along with those for other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, and researchers at the Bureau of Economic Geology, SMU and Texas A&M University, and it continues to monitor developments and research related to injection-induced seismicity.

Cleburne Area Multidisciplinary Integration of Findings

Engineering analysis is consistent with the Ellenburger formation's karstic nature and a fractured reservoir. Pressure gradient plot results indicate a potential for further fracturing occurring during disposal operations. A pattern of repeating cycles, increasingly difficult injection followed by enhanced ease of injection, was observed, with the decreased injectivity corresponding to seismic events.

The South Cleburne SWD 1 well was shut-in voluntarily during the RRC review in July 2009.

Since then, additional seismic events have occurred over a widespread area. One such cluster was caught with a temporary array of seismometers (June 2009 through June 2010) (Howe-Justinic et al., 2013) and was relocated, showing a clear cut fault in close proximity to the Cleburne Yard 1 well (Figure E-16). The well is located about 10 miles away from two large faults.

NORTH TEXAS AREA LESSONS LEARNED

- Publications (Howe-Justinic et al., 2013) indicate the optimal orientation for movement on a fault in the Barnett shale play area is north to south. The majority of the regional faults shown on Figure E-1 are oriented more northeast to southwest.
- The ability to identify short (2 to 3 km in length) faults is dependent on recording and relocating faults causing only small magnitude events. This is not possible using only the current seismometer network available in the north Texas area.
- Fine tuned relocation is possible when sufficient detail for the earth model in that specific area has been resolved.
    - Earthquake event relocation methodologies are undergoing development. The reviewed reports (Janská and Eisner, 2012; Reiter et al., 2012; Eisner, 2011; Frohlich et al., 2011) use different methods.
    - Several of the relocation methods require deploying a tightly spaced monitor network prior to the earthquake events.
    - Another of the relocation methods requires an existing network designed to record small, shallow seismic events. Recommended guidelines for this network configuration are available in Reiter et al. (2012).
- While many of these temporary networks are connected to one of the major seismic database catalogs, the reinterpretation is not typically uploaded. Therefore relocated interpretation data is not available until after the associated publication has been released. This can be 2 to 3 years after the events.
- Initiating dialogue with operators can result in early voluntary action, including well shut-in or acquisition of additional site data.
    - Initiating dialogue between the operator and UIC regulator resulted in the voluntary shut-in of some suspect disposal wells.
    - For example, an operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep-seated fault.
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.

    - Hall integral and derivative plots may indicate a no-flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance; or possible response from offset disposal wells.
    - Hall integral and derivative plots may illustrate enhanced injectivity.
    - Hall integral and derivative plots showing repeated cycles of increasingly difficult injection followed by enhanced ease of injection may indicate a correspondence between decreased injectivity and seismic events.
- Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation or encountering an increased permeability zone at distance.
- Conducting a falloff test can further refine the reservoir characterization.
    - Fractured flow behavior was confirmed from the falloff test analyses for the Ellenburger disposal zone in a Cleburne area well.
- Increased seismic monitoring stations may be warranted to pinpoint active fault locations and increase detection of smaller events.
    - Additional stations installed resulted in reliable identification of active fault locations.
- A multidisciplinary combined approach to minimize and manage induced seismicity at a given location may be helpful.
    - Working with state geological survey or university researchers provided expert consultation, resulted in installation of additional seismometers and yielded a clearer understanding of the deep seated active faulting.
- Director discretionary authority was used to solve individual site-specific concerns:
    - The Director acquired additional site information and evaluated voluntary action of operators.

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FIGURE E- 1: NORTH TEXAS CASE STUDY REGIONAL AREA

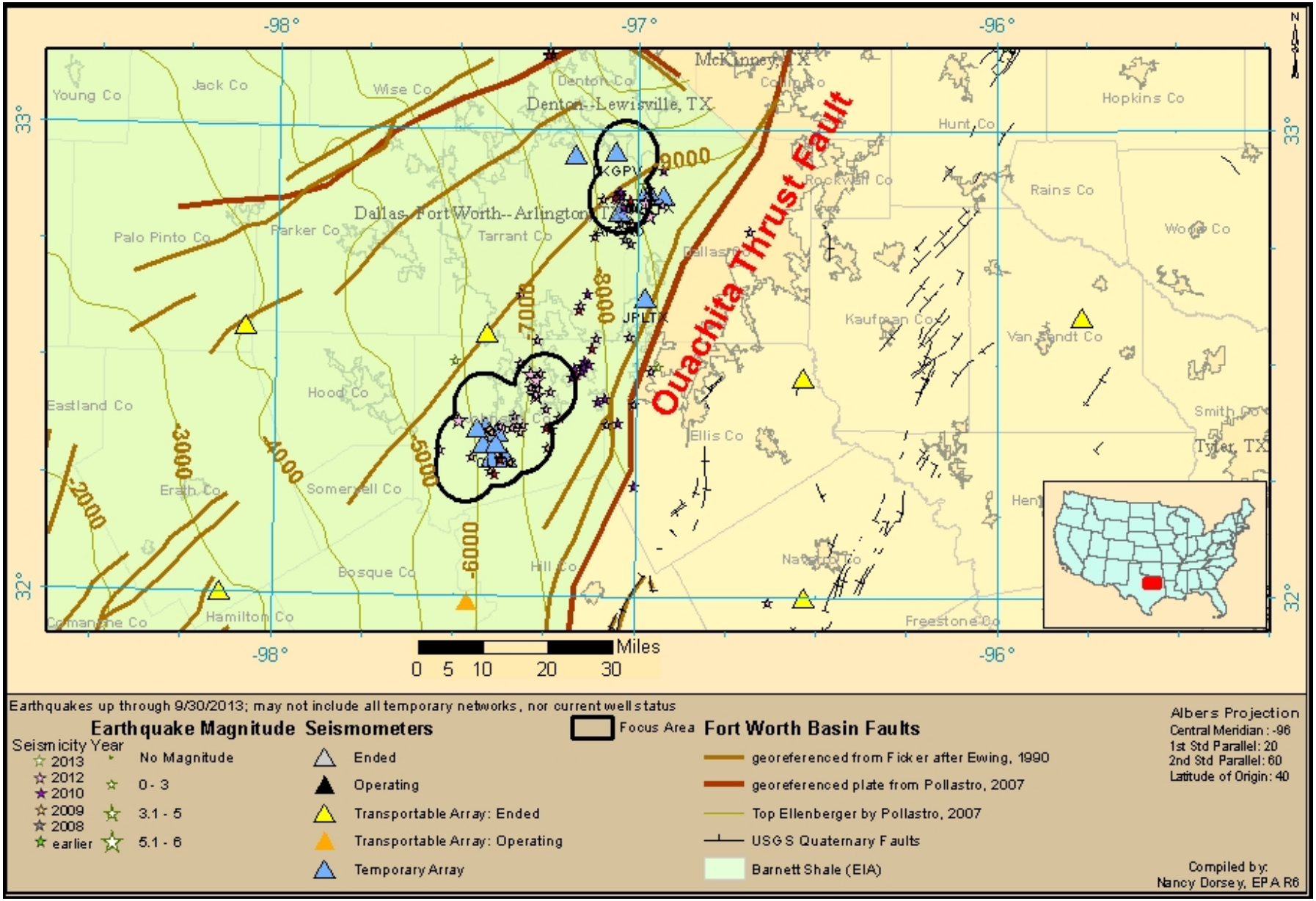
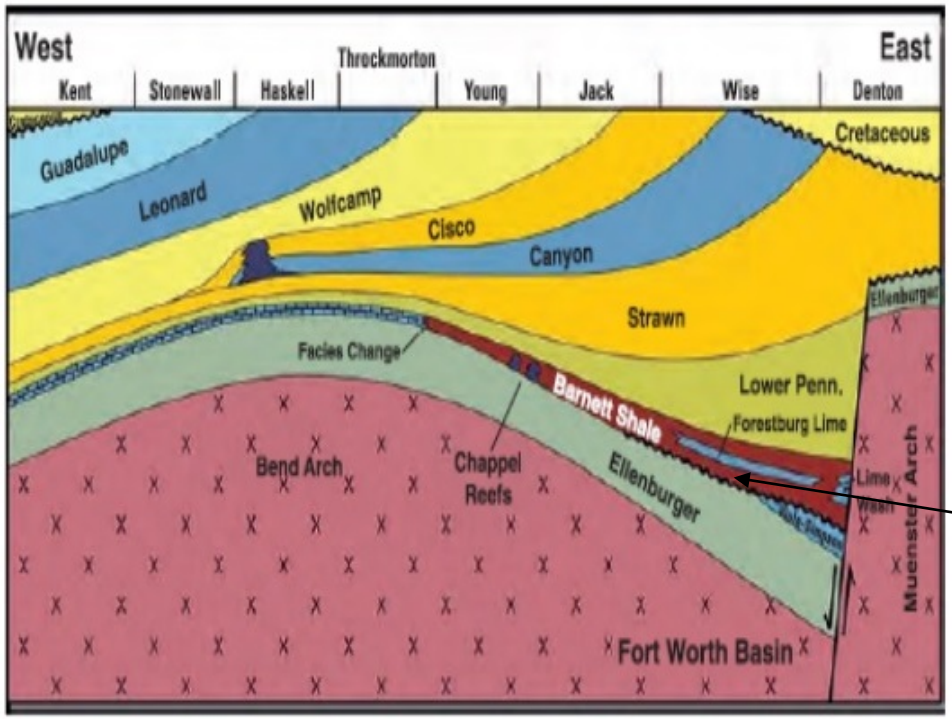


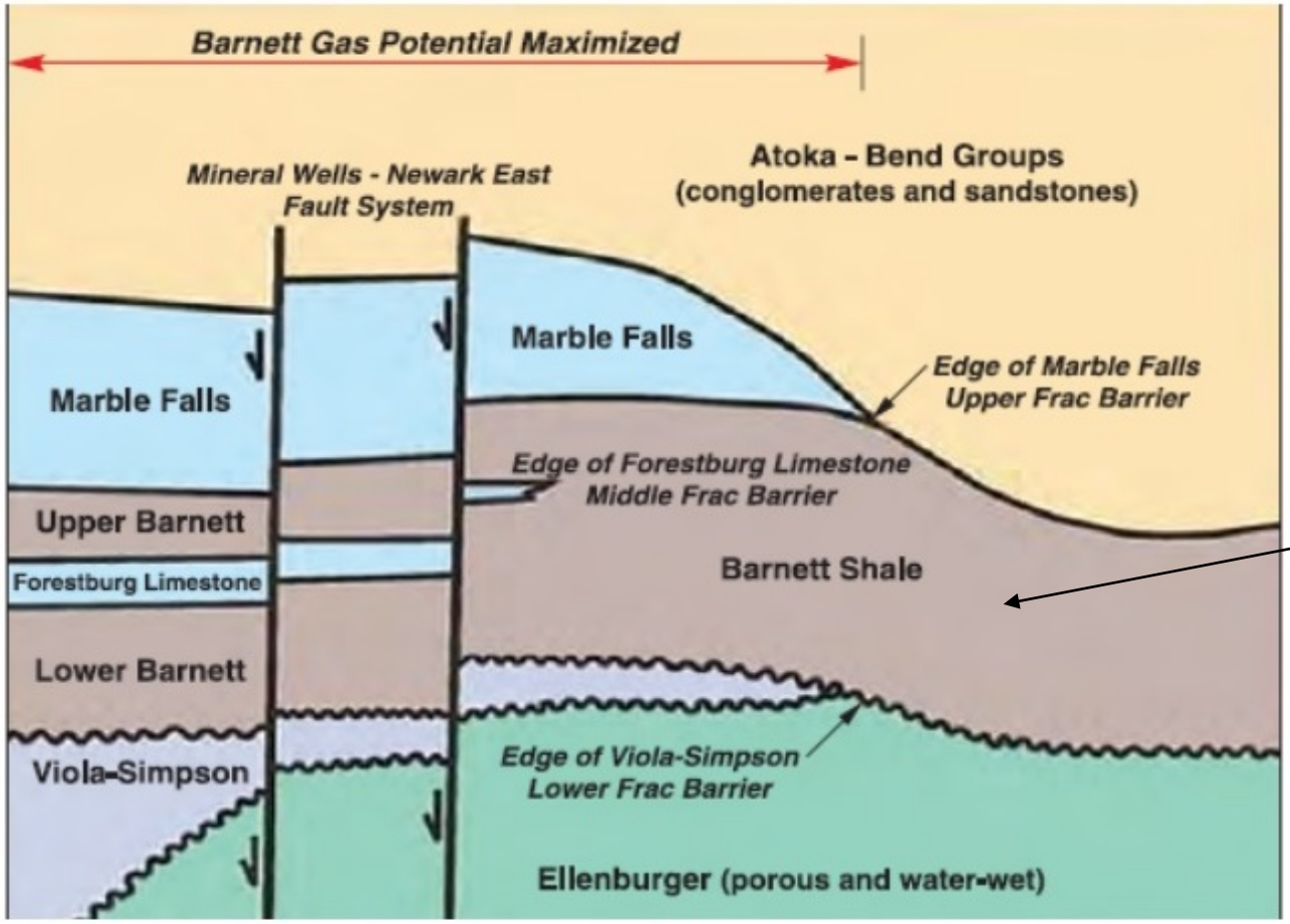
FIGURE E- 2: BARNETT SHALE, E-W GENERALIZED CROSS-SECTION (BRUNER AND SMOSNA, 2011)



Barnett shale overlying the Ellenburger formation

Bruner, K. R., and Smosna, R., 2011, A comparative study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin: US Department of Energy, National Energy Technology Laboratory.

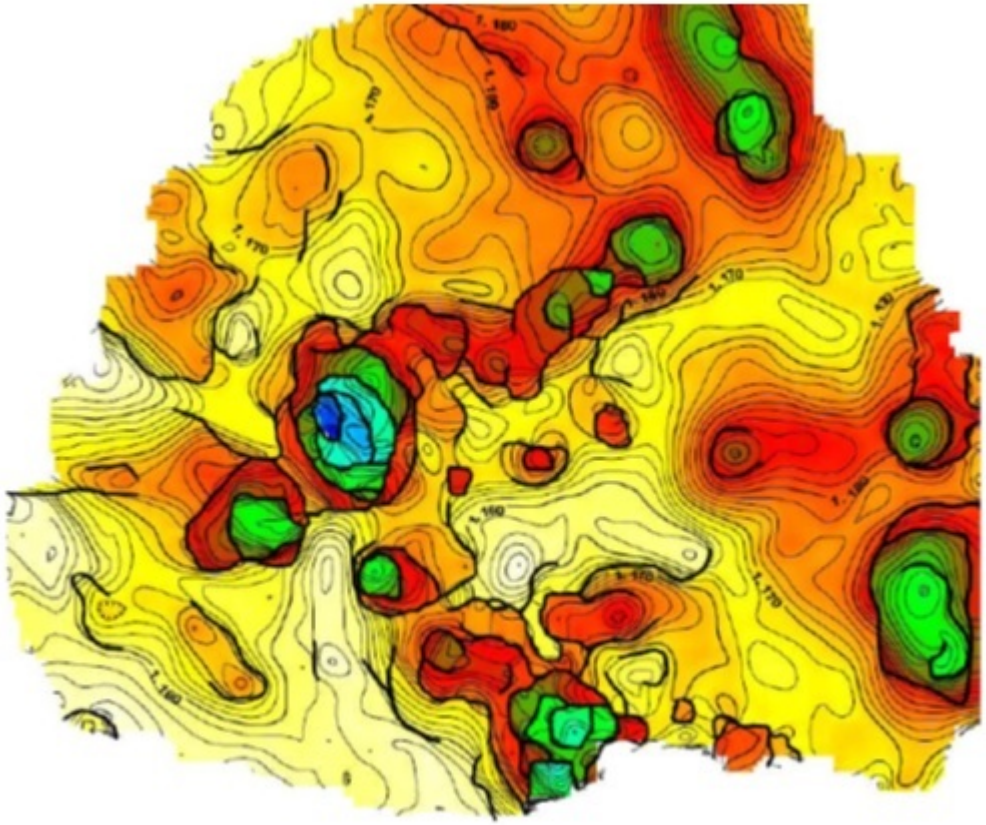
FIGURE E- 3: BARNETT SHALE, N-S GENERALIZED CROSS-SECTION (BRUNER AND SMOSNA, 2011)



Barnett shale overlying the Ellenburger formation

Bruner, K. R., and Smosna, R., 2011, A comparative study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin: US Department of Energy, National Energy Technology Laboratory.

FIGURE E- 4: TOP ELLENBURGER KARST FEATURES FROM 3D



Steward, D. B., 2011, The Barnett Shale oil model of North Texas, Article #110151, Search and Discovery, AAPG/Datapages, Inc., posted June 13, 2011.

FIGURE E- 5: DFW FAULT LOCATION (FROHLICH ET AL., 2011)

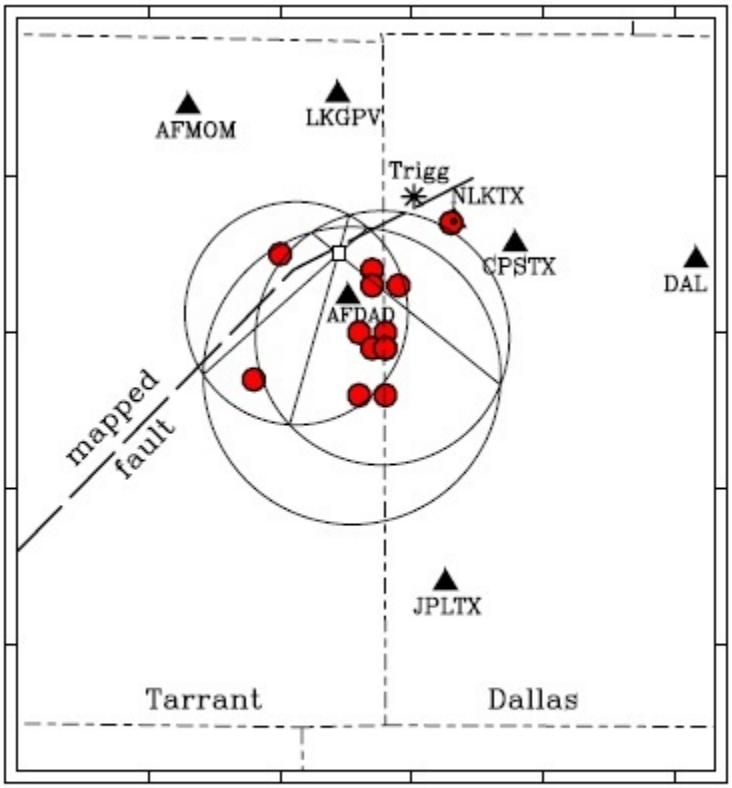


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FIGURE E- 6: DFW FOCUS AREA SEISMICITY MAP

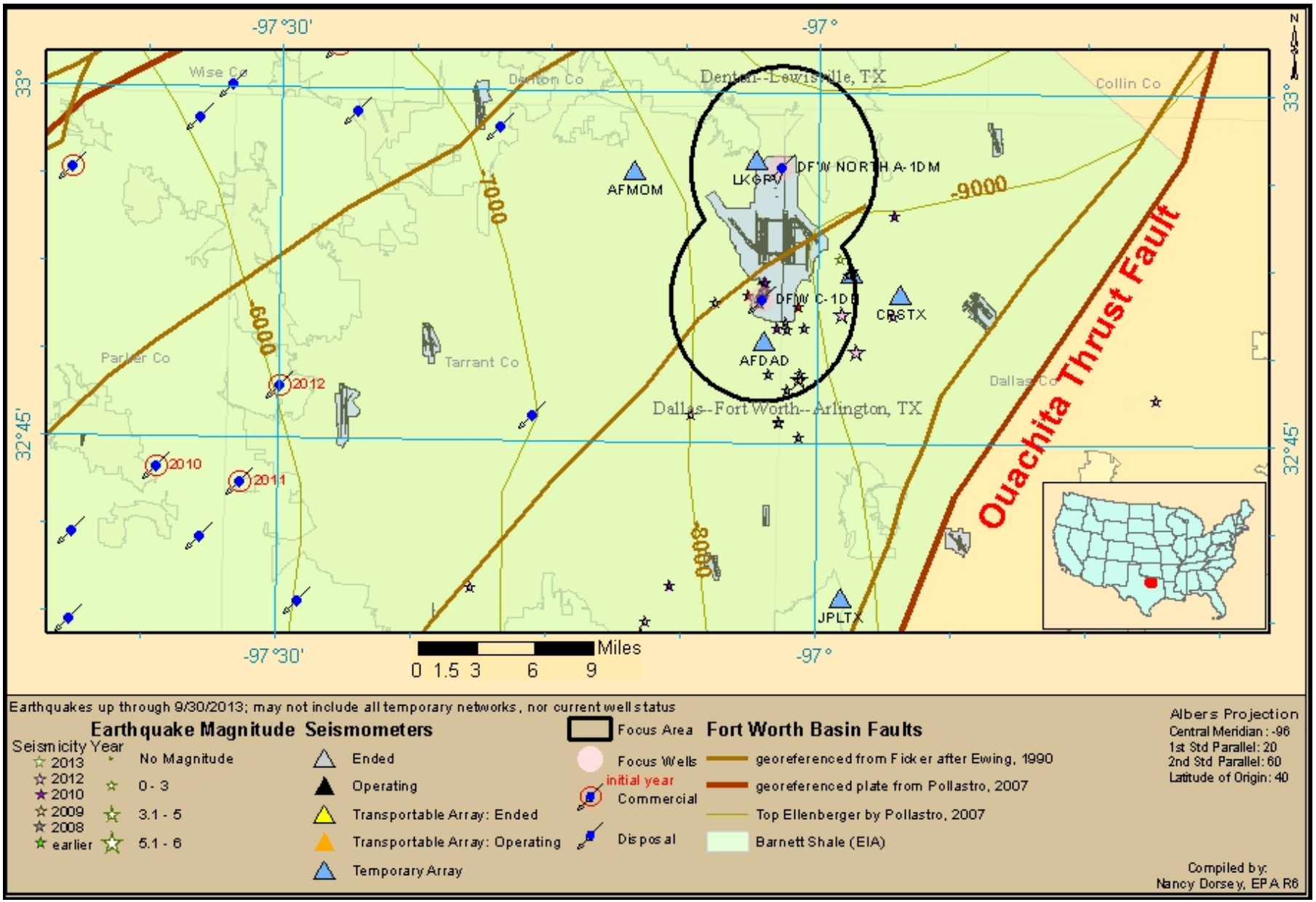


FIGURE E- 7: RELOCATED DFW EVENTS (FIGURE 5 OF JANSKÁ AND EISNER, 2012)

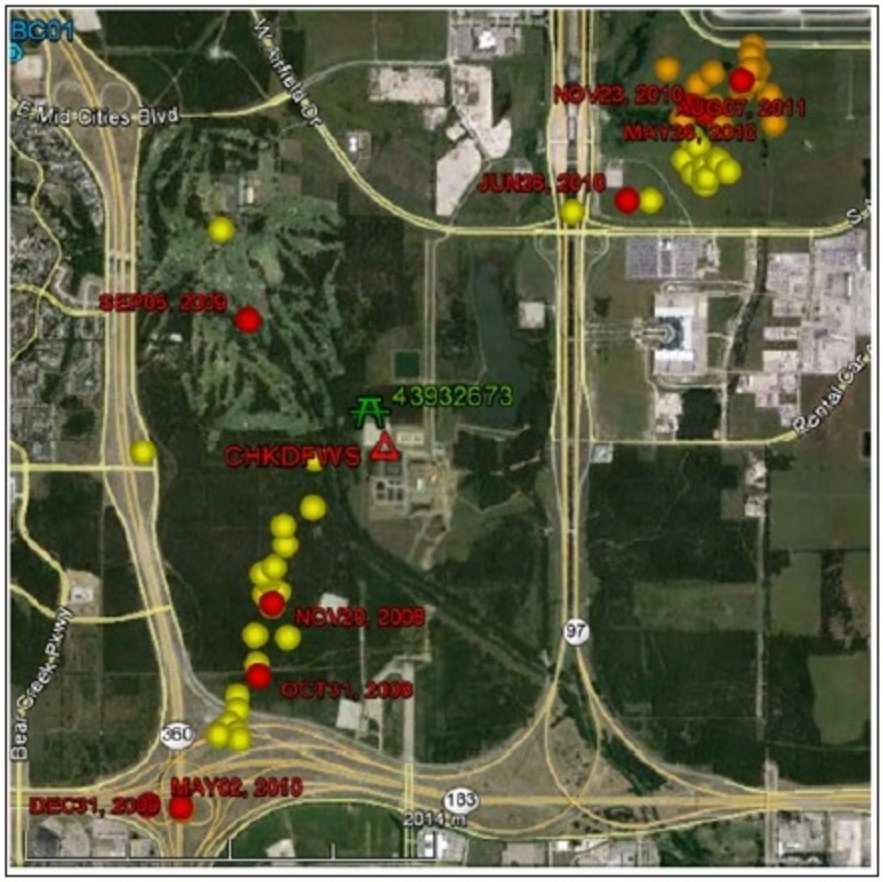


Figure 5. *Seismic events located in the DFW area. Yellow points show epicenters of events located by 2D relative location, orange points by 3D relative location. Red points refer to the detection masters. The CHKDFWS station is on the site of the SWD well (*API *43932673).*

Janská, E. and L. Eisner, 2012, Ongoing Seismicity in the Dallas-Fort Worth Area: The Leading Edge, v. 31, p. 1462-1468.
http://dx.doi.org/10.1190/tle31121462.1

FIGURE E- 8: DFW SEISMOMETER DEPLOYMENT (FIGURE 1 OF JANSKÁ AND EISNER, 2012)

Figure 1. *Dallas-Fort Worth (DFW) area and regional seismic WMOK and TA.135A stations in lower right inset. Red and green triangles represent currently recording stations. Yellow triangles represent temporary stations operated by South Methodist University (SMU). The picnic table symbol stands for the injection well (API 43932673).*

Janská, E. and L. Eisner, 2012, Ongoing Seismicity in the Dallas-Fort Worth Area: The Leading Edge, v. 31, p. 1462-1468.
http://dx.doi.org/10.1190/tle31121462.1

FIGURE E- 9: DFW FOCUS AREA SEISMICITY TIMELINE

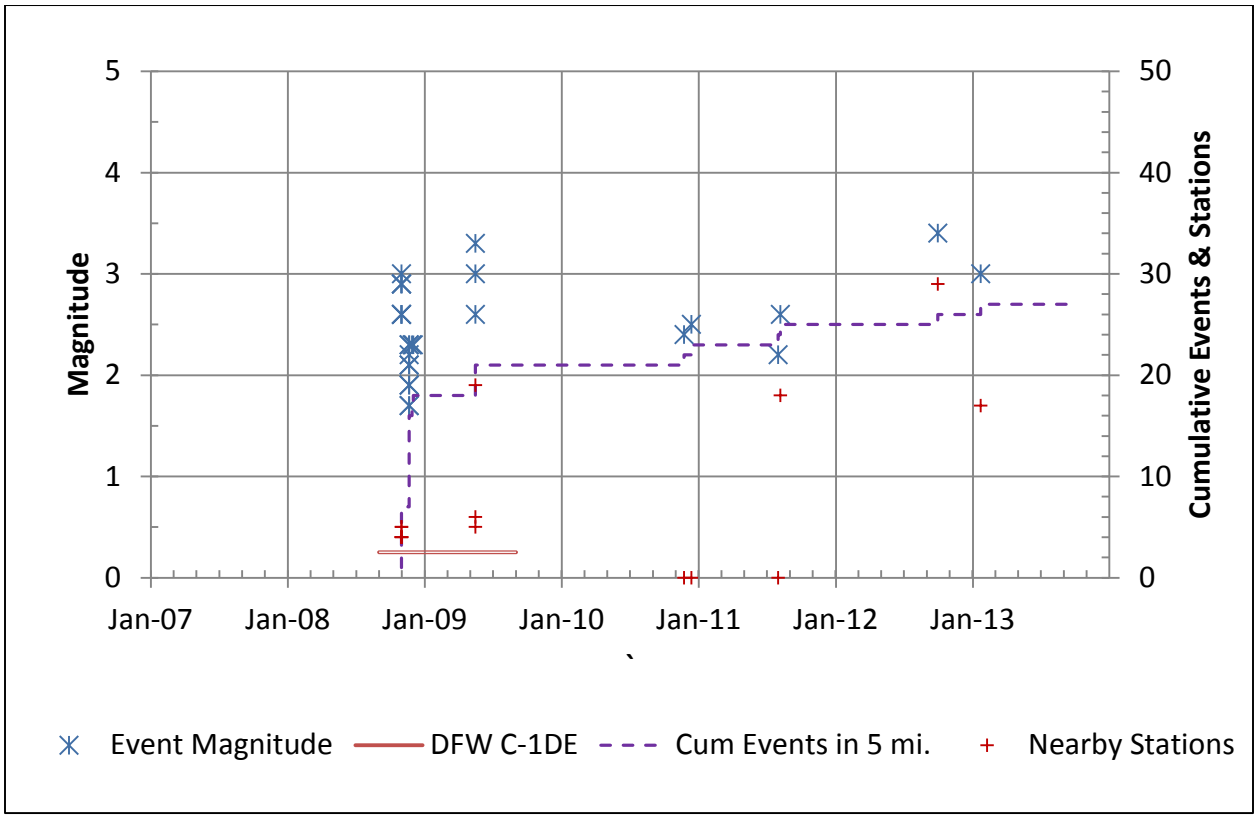


FIGURE E- 10: DFW C1DE OPERATIONAL DATA OVERVVIEW PLOT

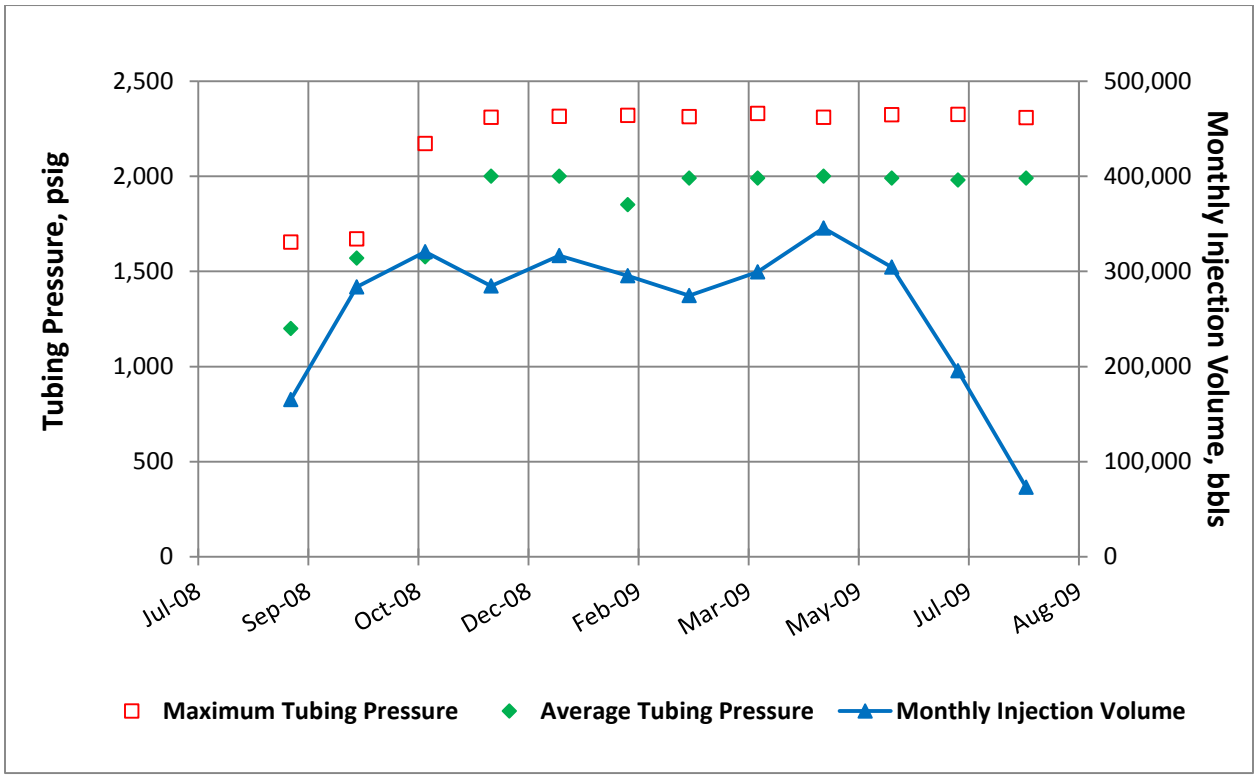


FIGURE E- 11: DFW NORTH A1DM OPERATIONAL DATA OVERVIEW PLOT

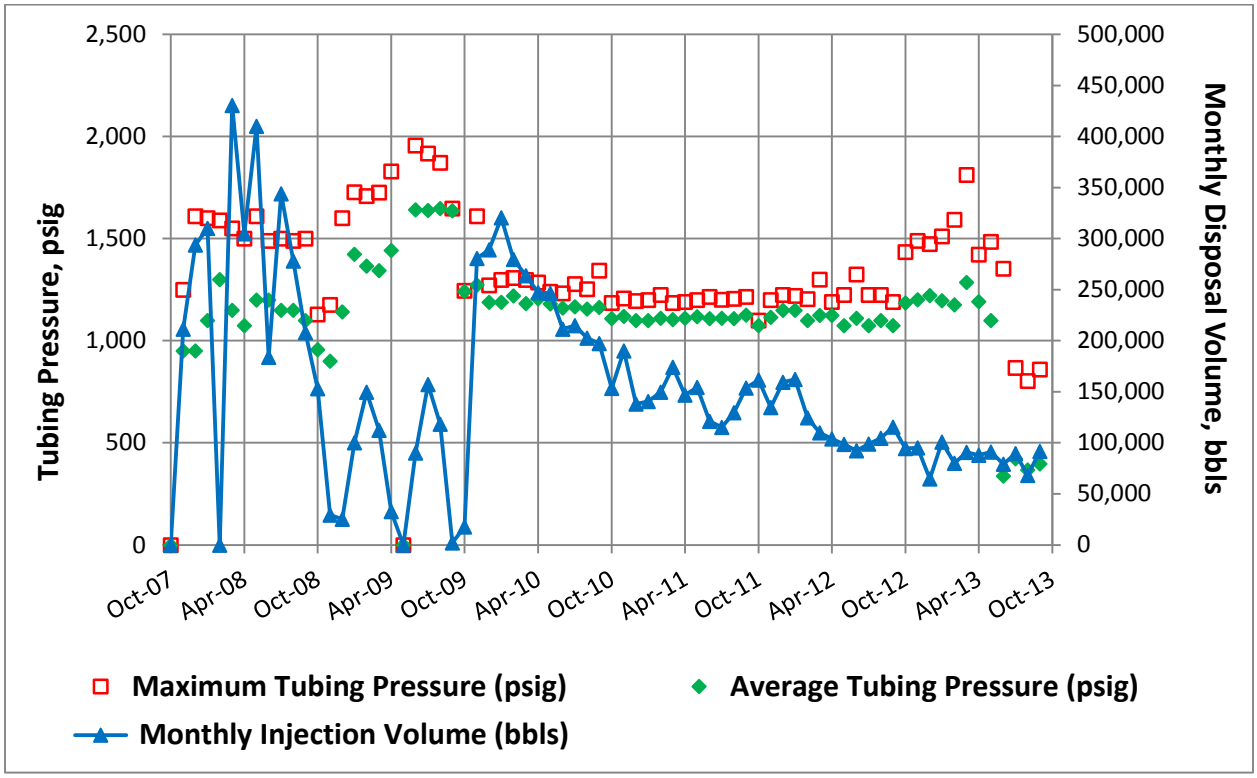


FIGURE E- 12: DFW C1DE OPERATIONAL PRESSURE GRADIENT PLOT

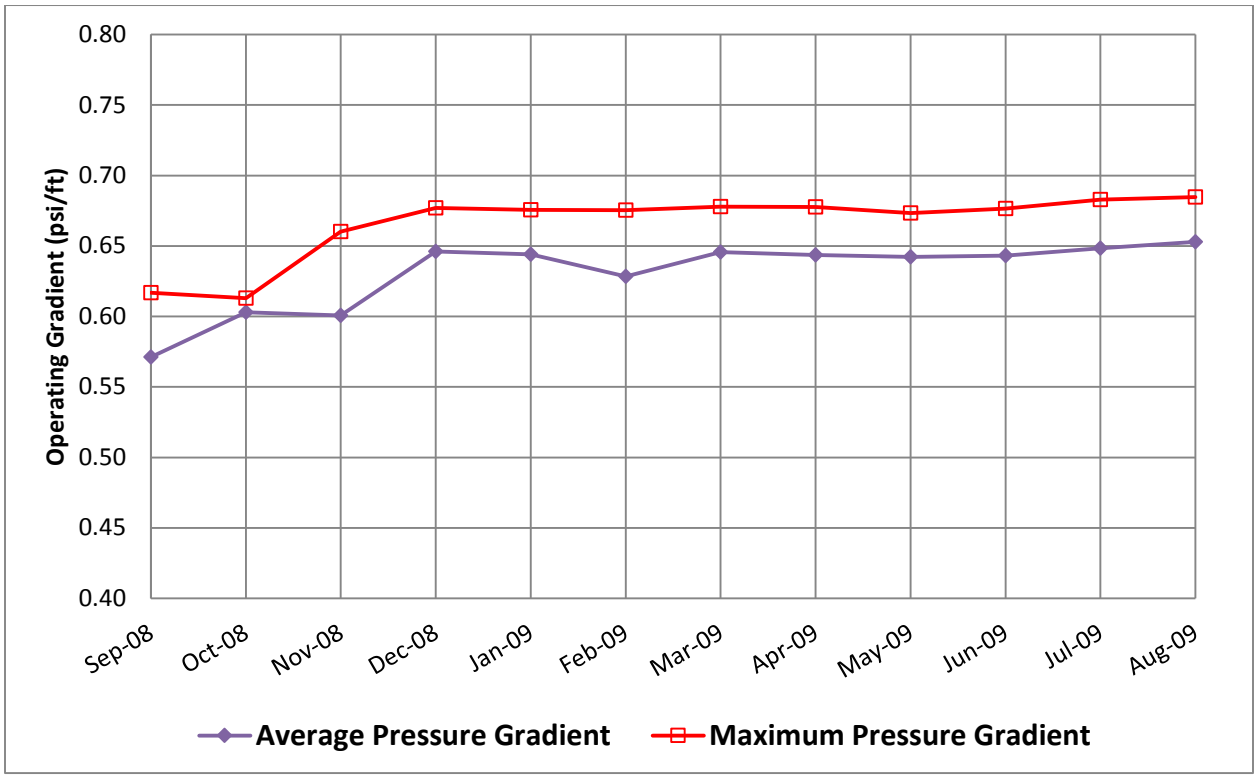


FIGURE E- 13: DFW NORTH A1DM OPERATIONAL PRESSURE GRADIENT PLOT

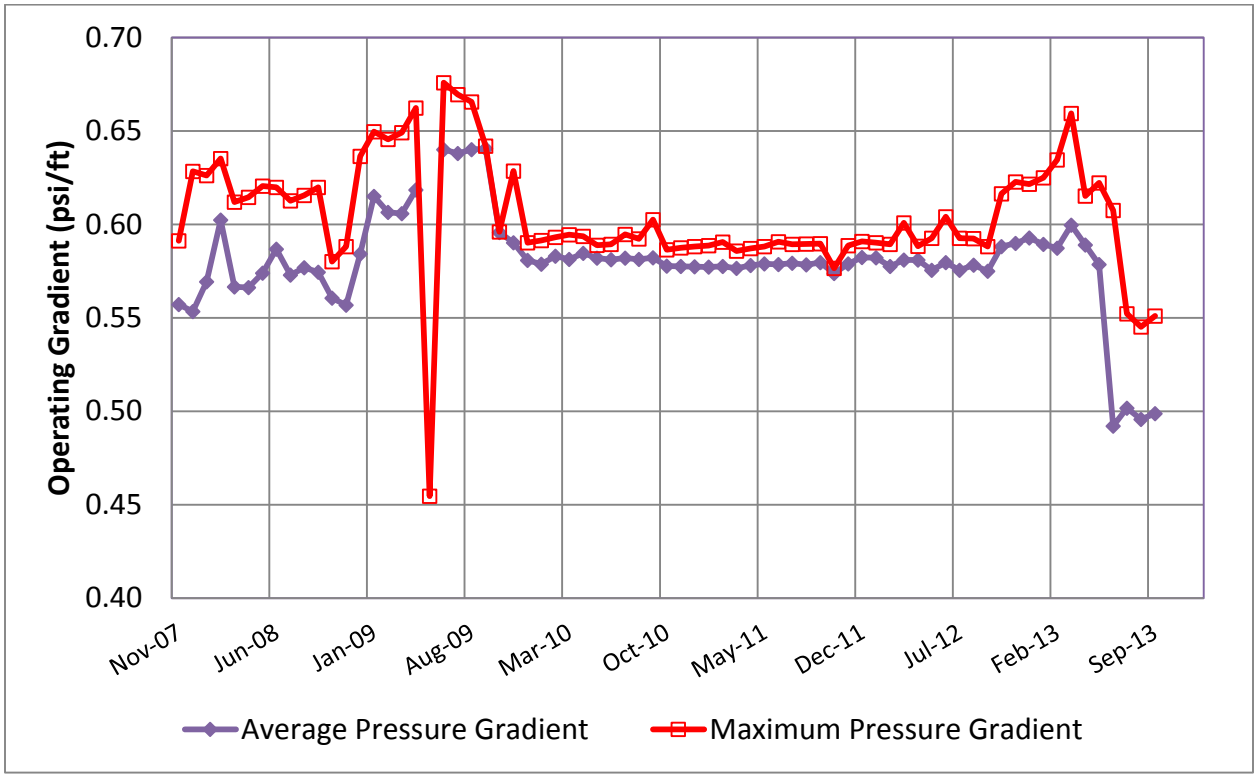


FIGURE E- 14: DFW C1DE TANDEM PLOT OF HALL INTEGRAL WITH DERIVATIVE AND SEISMIC EVENTS

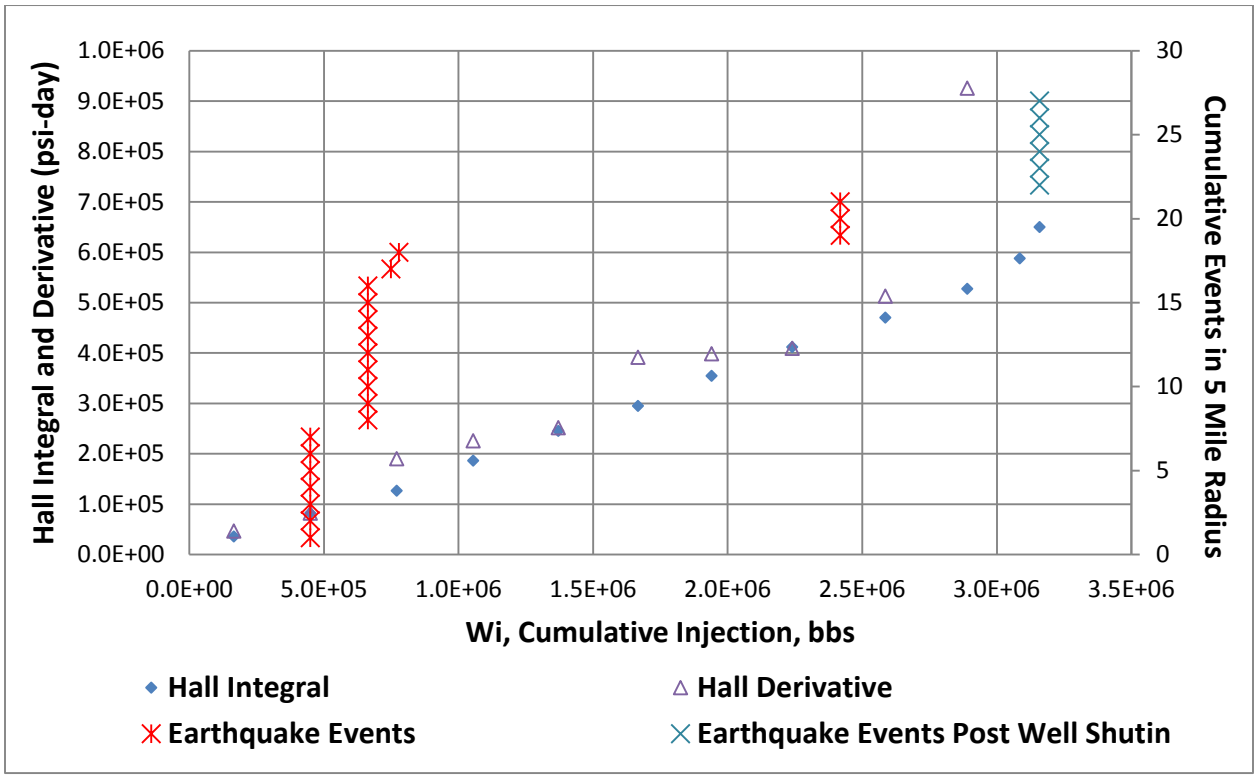


FIGURE E- 15: DFW NORTH A1DM HALL INTEGRAL AND DERIVATIVE PLOT

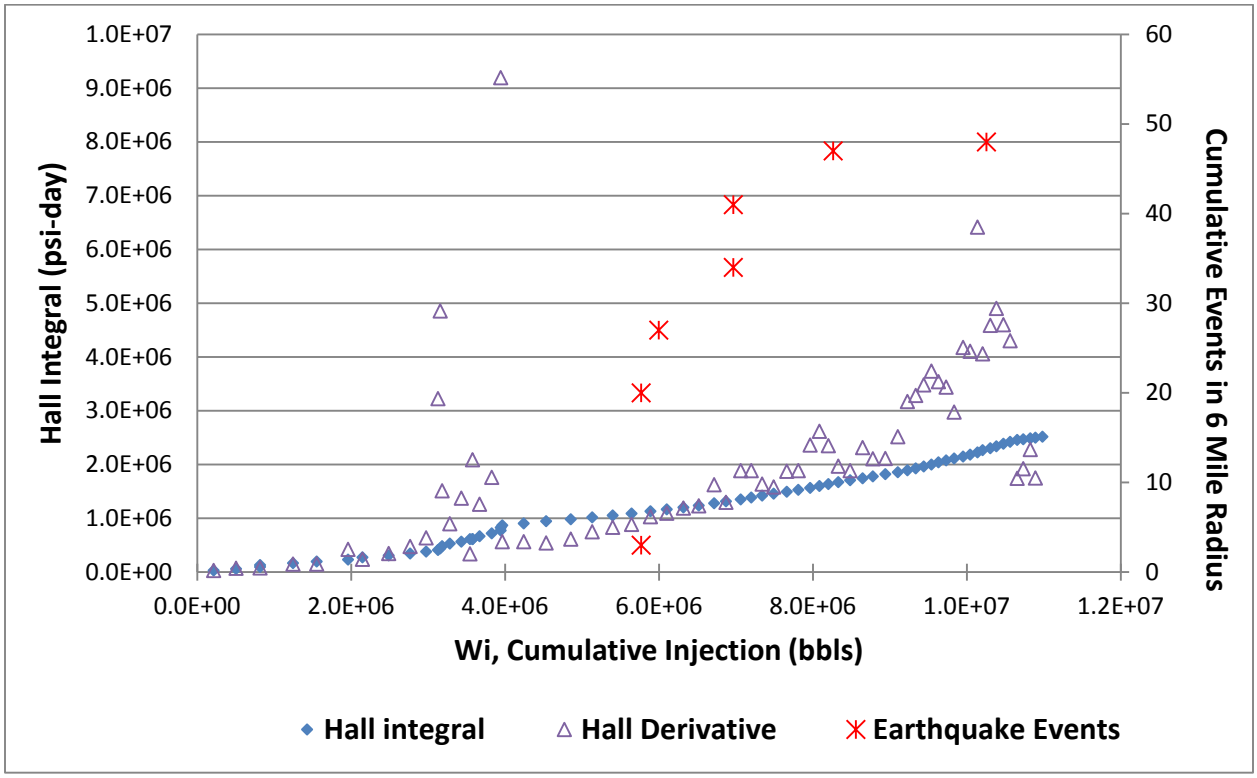


FIGURE E- 16: CLEBURNE FOCUS AREA SEISMICITY MAP

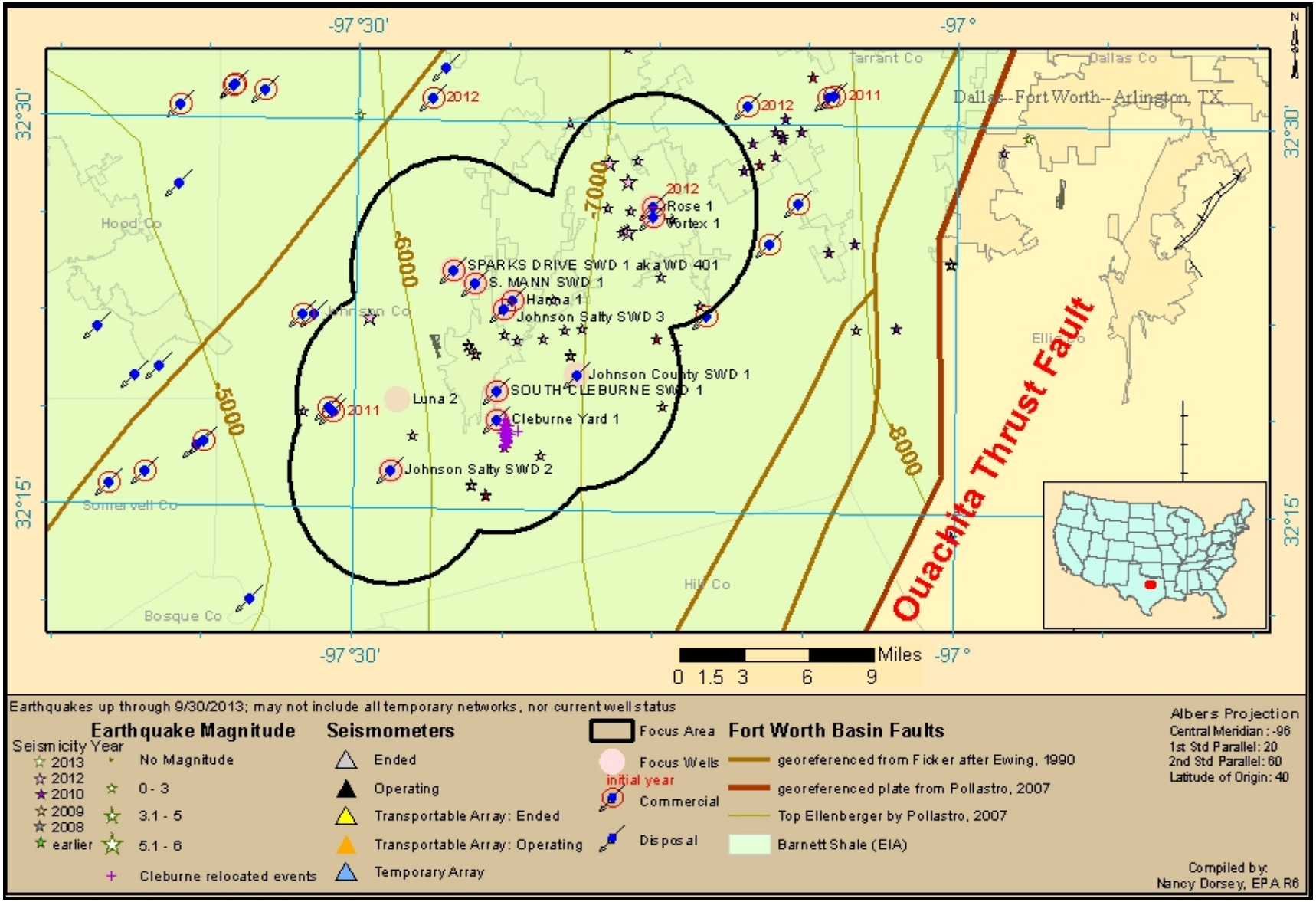


FIGURE E- 17: CLEBURNE FOCUS AREA SEISMICITY TIMELINE

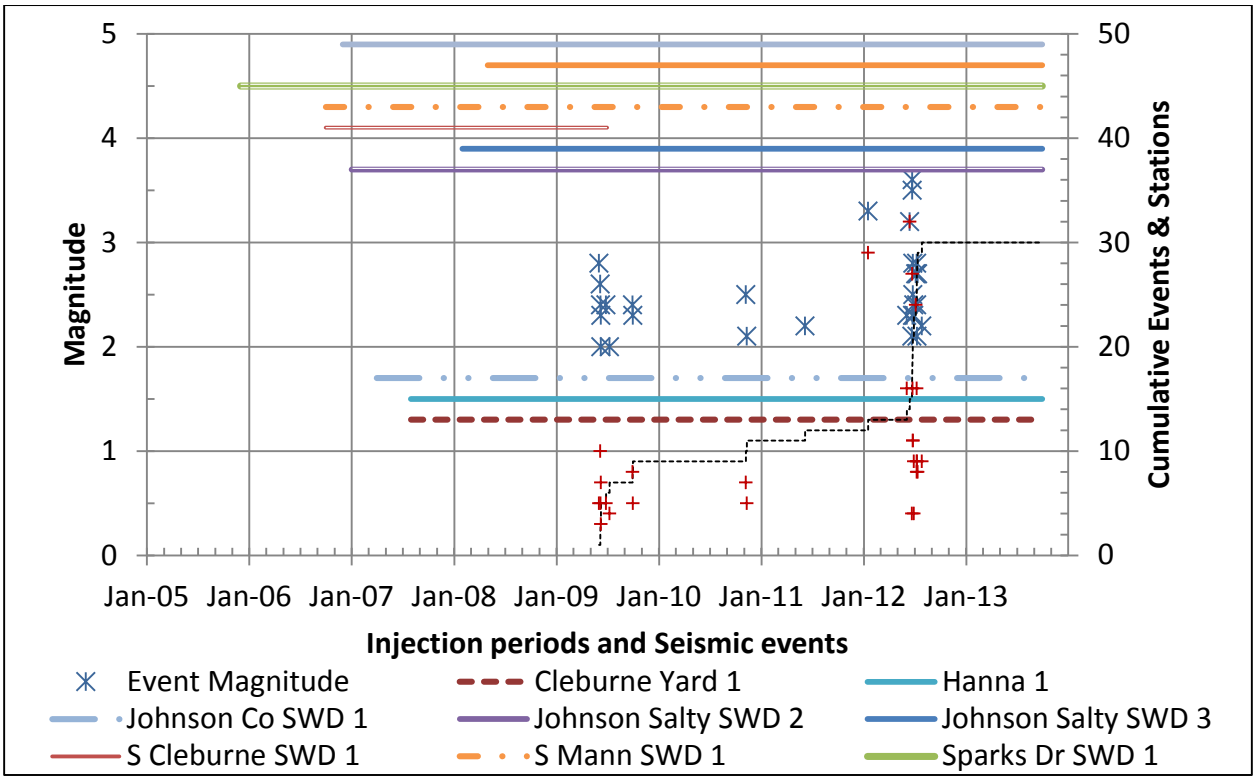


FIGURE E- 18: CLEBURNE SEISMOMETER DEPLOYMENT AND EVENT RELOCATION (FIGURE 4 OF HOWE-JUSTINIC ET AL., 2013)

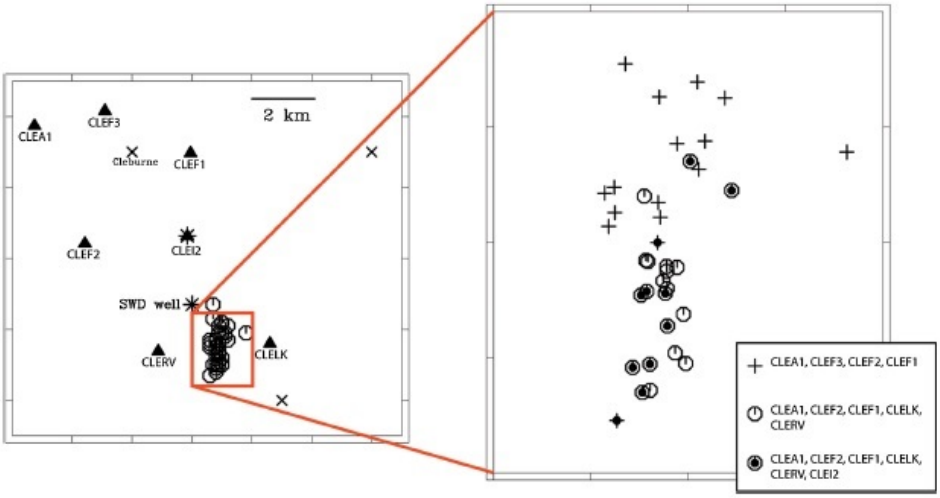


Figure 4. Final event locations determined from data recorded by the local network. Triangles are seismic stations; plus symbols, octagons; circles, earthquakes; and asterisks, injection disposal wells. Events located using data from the initial four stations (plus symbols) are more northward. Events locations using the final network configuration (circles) should be more reliable because stations surrounded the events. Note that locations form an approximate north–south trend about 2 km long, with a saltwater disposal well (API 42-251-31266) situated about 1.3 km from the trend.

Howe Justinic, A. M., B. S. Stump, C. Hayward, and C. Frohlich (2013). Analysis of the Cleburne earthquake sequence from June 2009 to June 2010: Bulletin of the Seismological Society of America, v. 103 n. 6, p. 3083-3093. doi: 10.1785/0120120336

FIGURE E- 19: HANNA OPERATIONAL DATA OVERVIEW PLOT

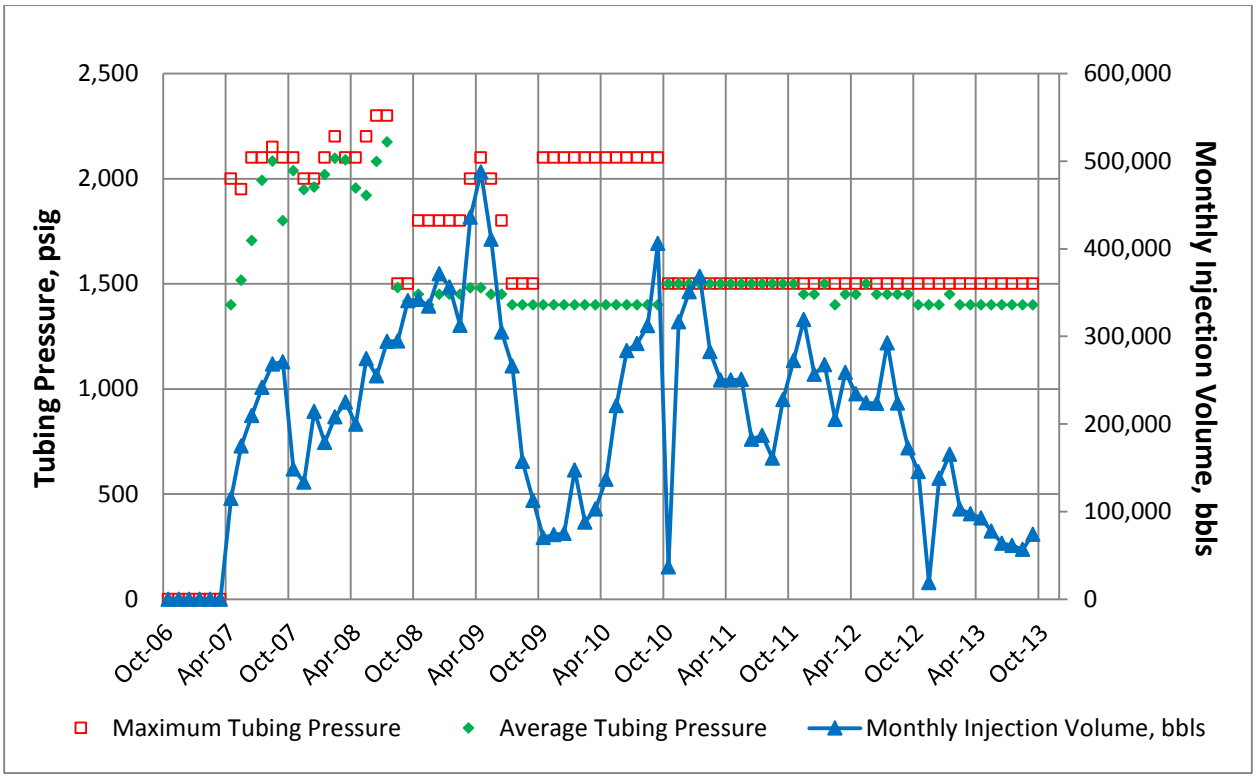


FIGURE E- 20: JOHNSON SALTY III OPERATIONAL DATA OVERVIEW PLOT

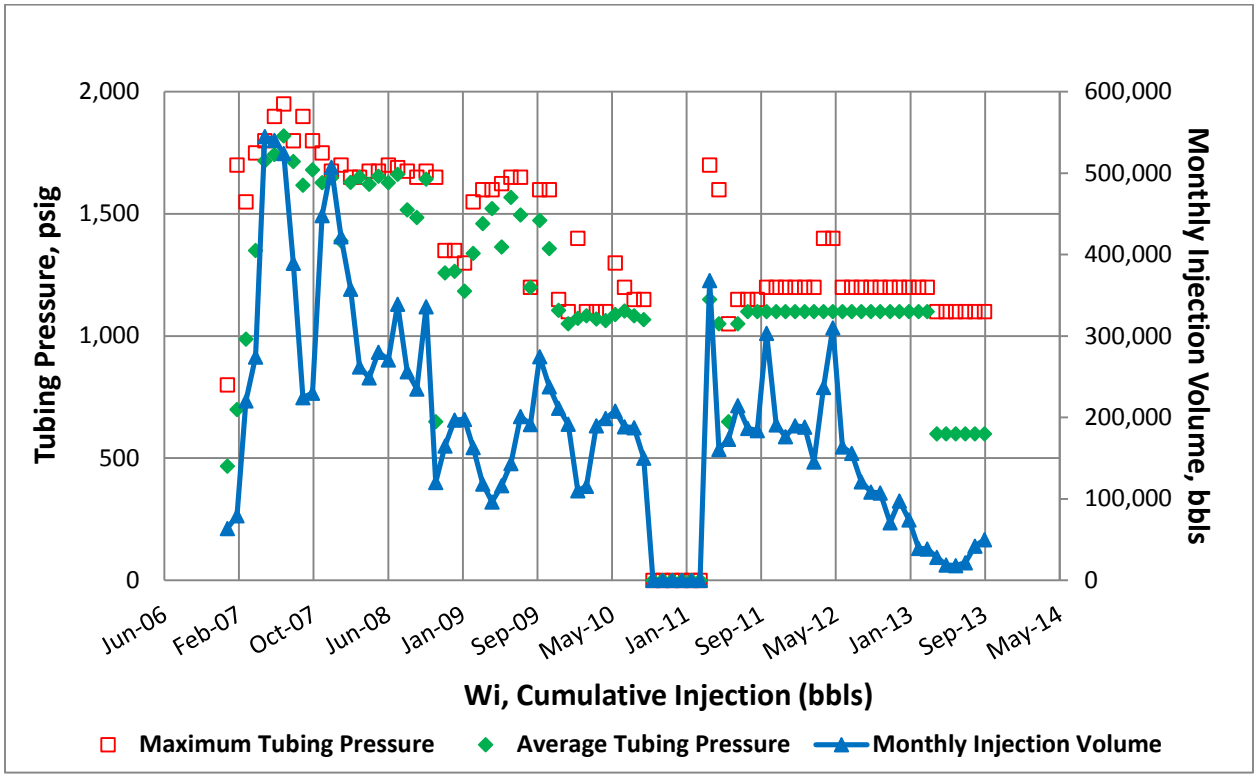


FIGURE E- 21: ROSE OPERATIONAL DATA OVERVIEW PLOT

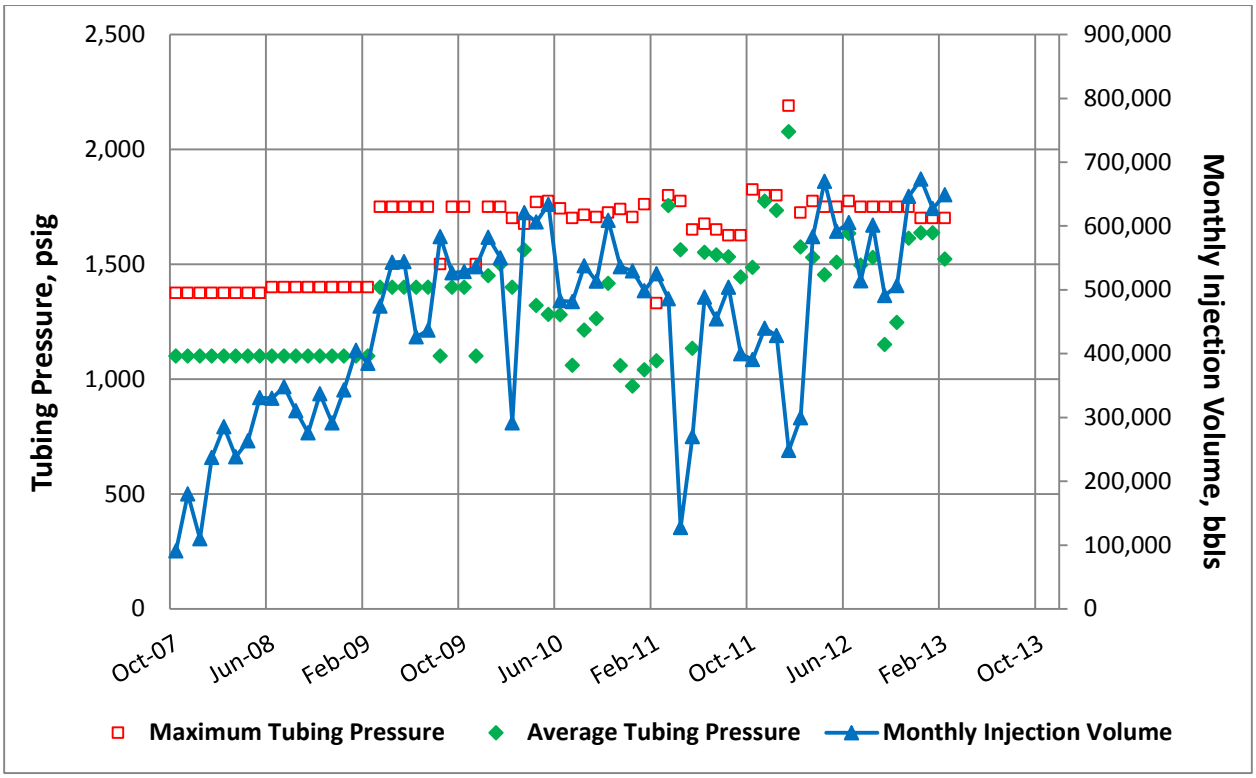


FIGURE E- 22: VORTEX OPERATIONAL DATA OVERVIEW PLOT

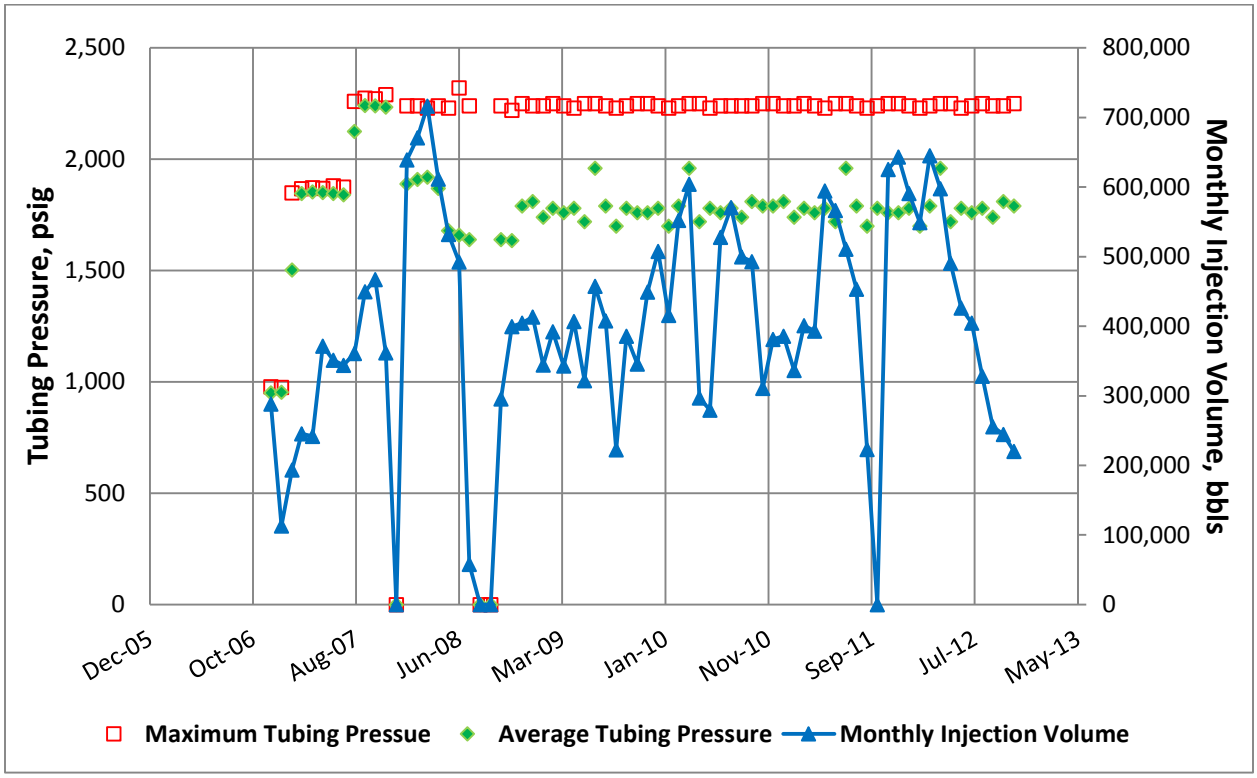


FIGURE E- 23: MANN OPERATIONAL DATA OVERVIEW PLOT

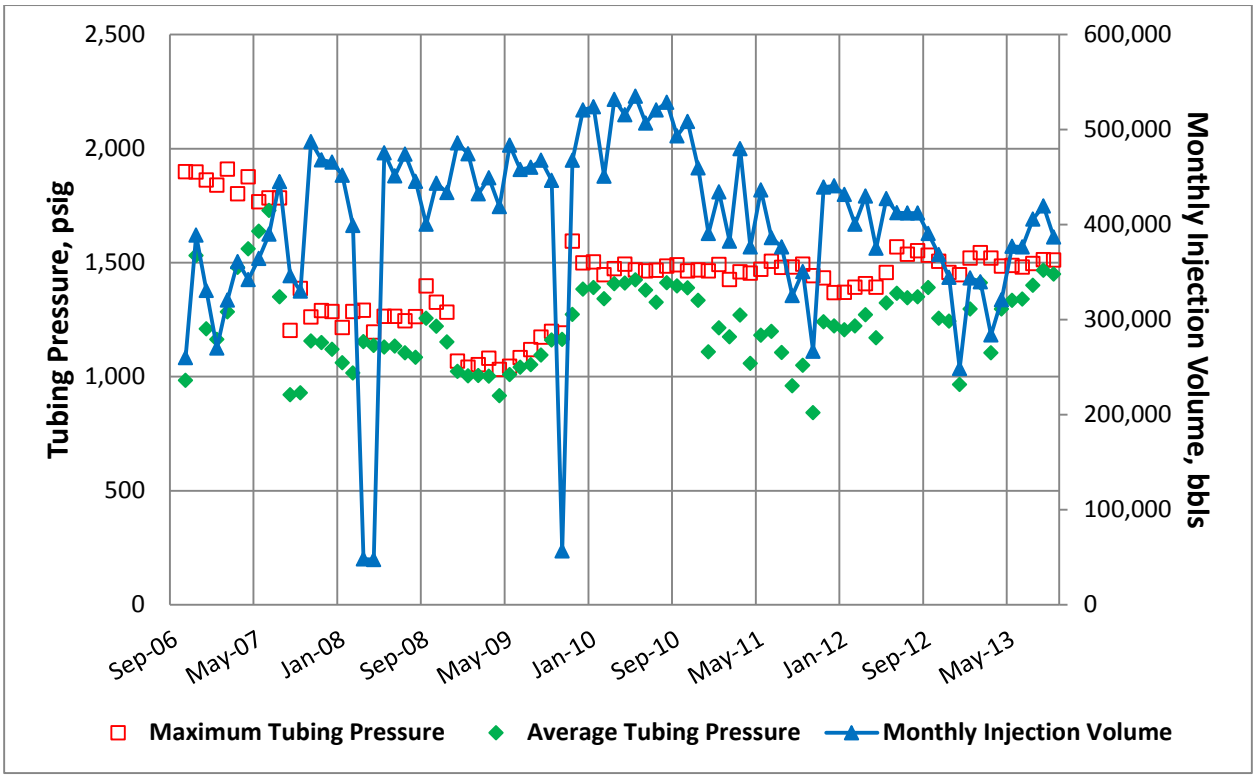


FIGURE E- 24: SPARKS DRIVE OPERATIONAL DATA OVERVIEW PLOT

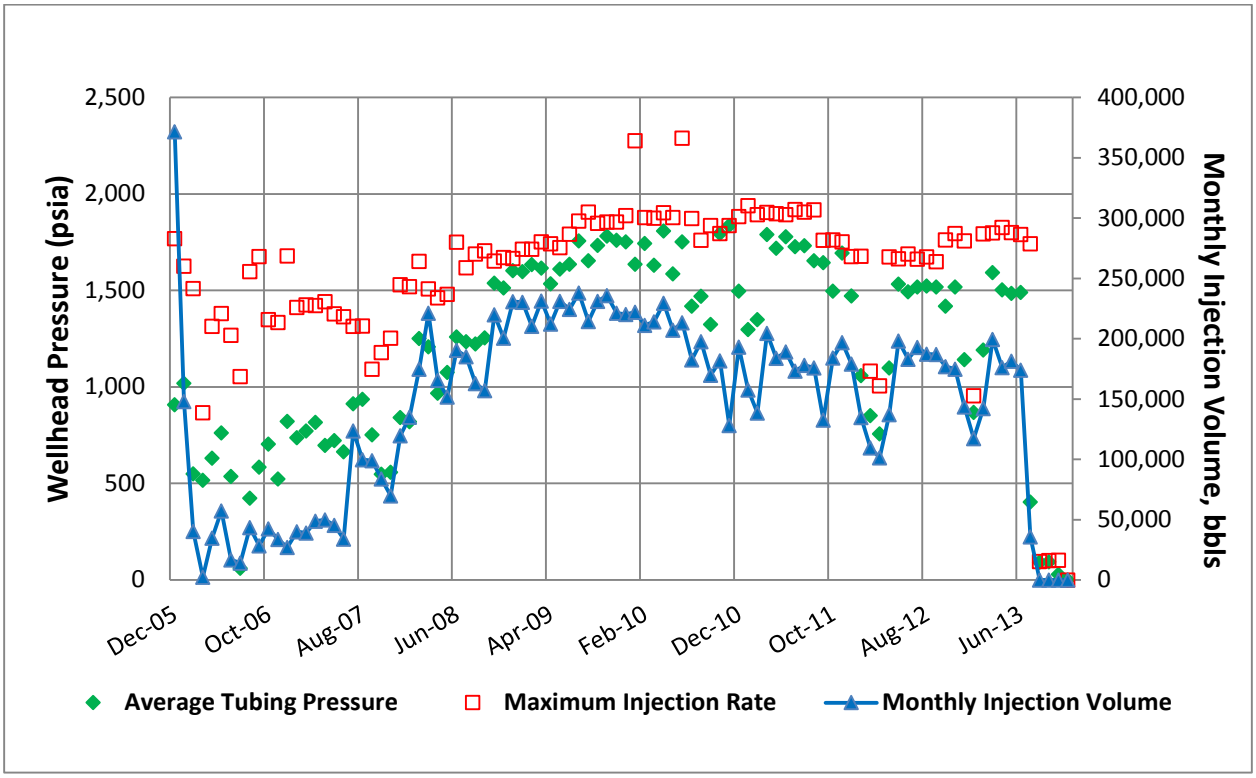


FIGURE E- 25: JOHNSON COUNTY OPERATIONAL DATA OVERVIEW PLOT

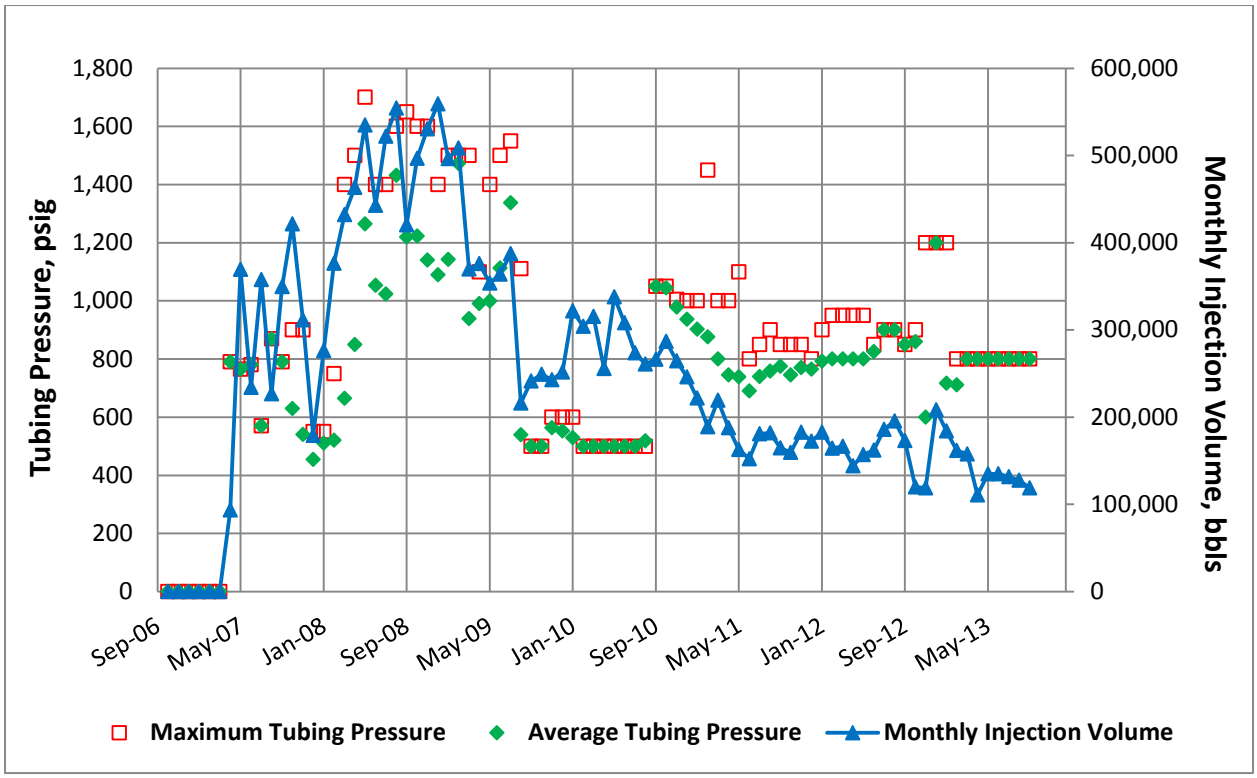


FIGURE E- 26: SOUTH CLEBURNE OPERATIONAL DATA OVERVIEW PLOT

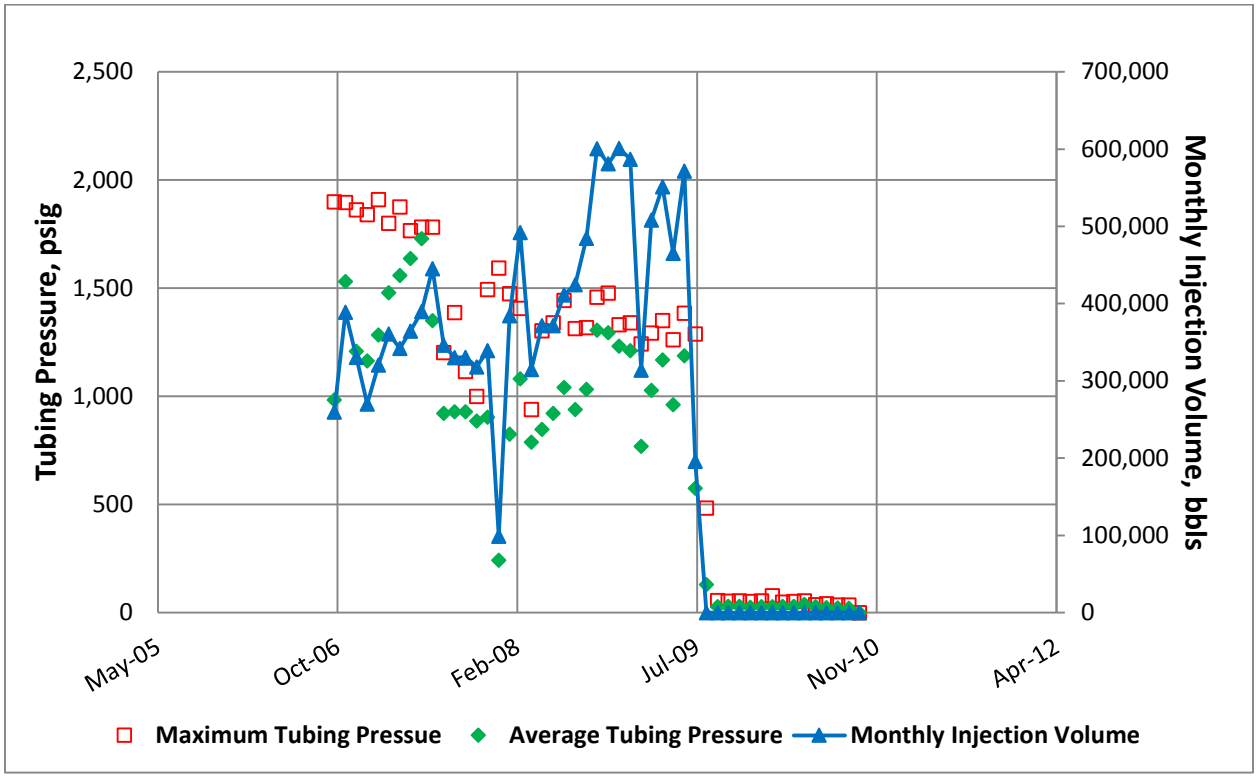


FIGURE E- 27: CLEBURNE YARD OPERATIONAL DATA OVERVIEW PLOT

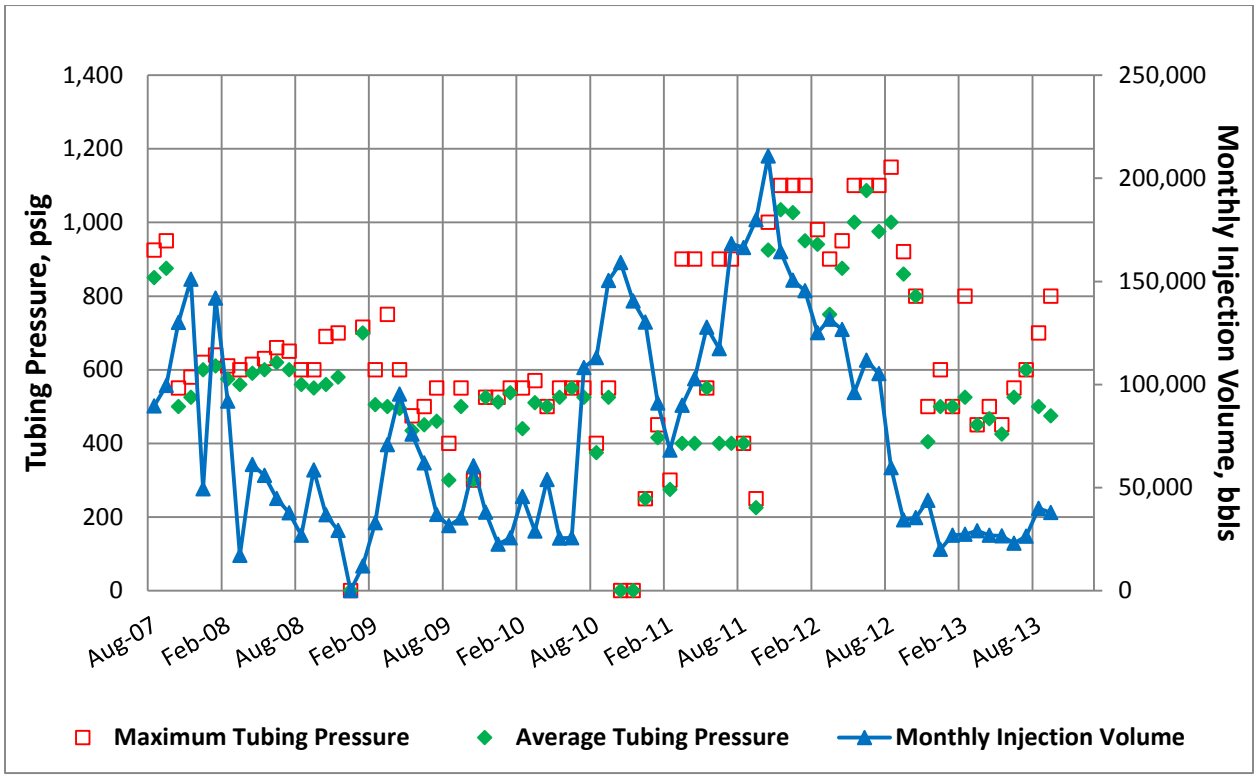


FIGURE E- 28: JOHNSON SALTY II OPERATIONAL DATA OVERVIEW PLOT

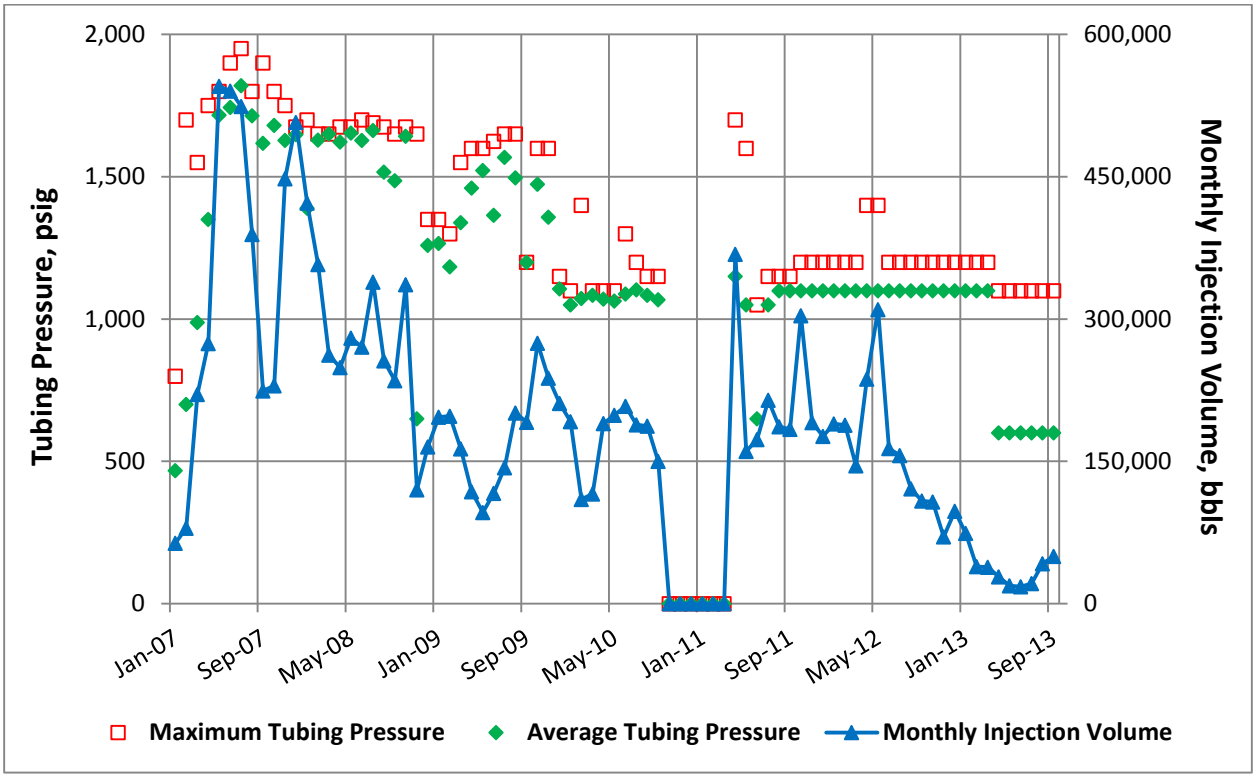


FIGURE E- 29: HANNA OPERATING PRESSURE GRADIENT PLOT

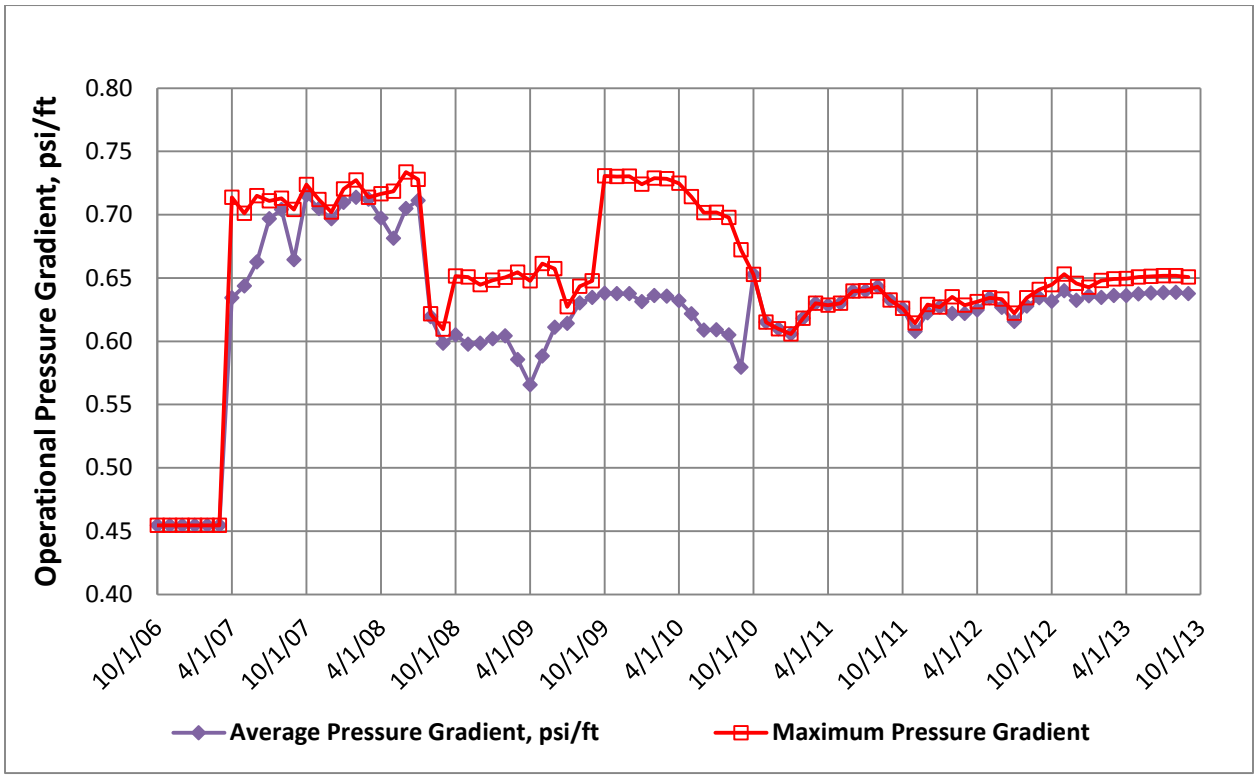


FIGURE E- 30: JOHNSON SALTY III OPERATIONAL PRESSURE GRADIENT PLOT

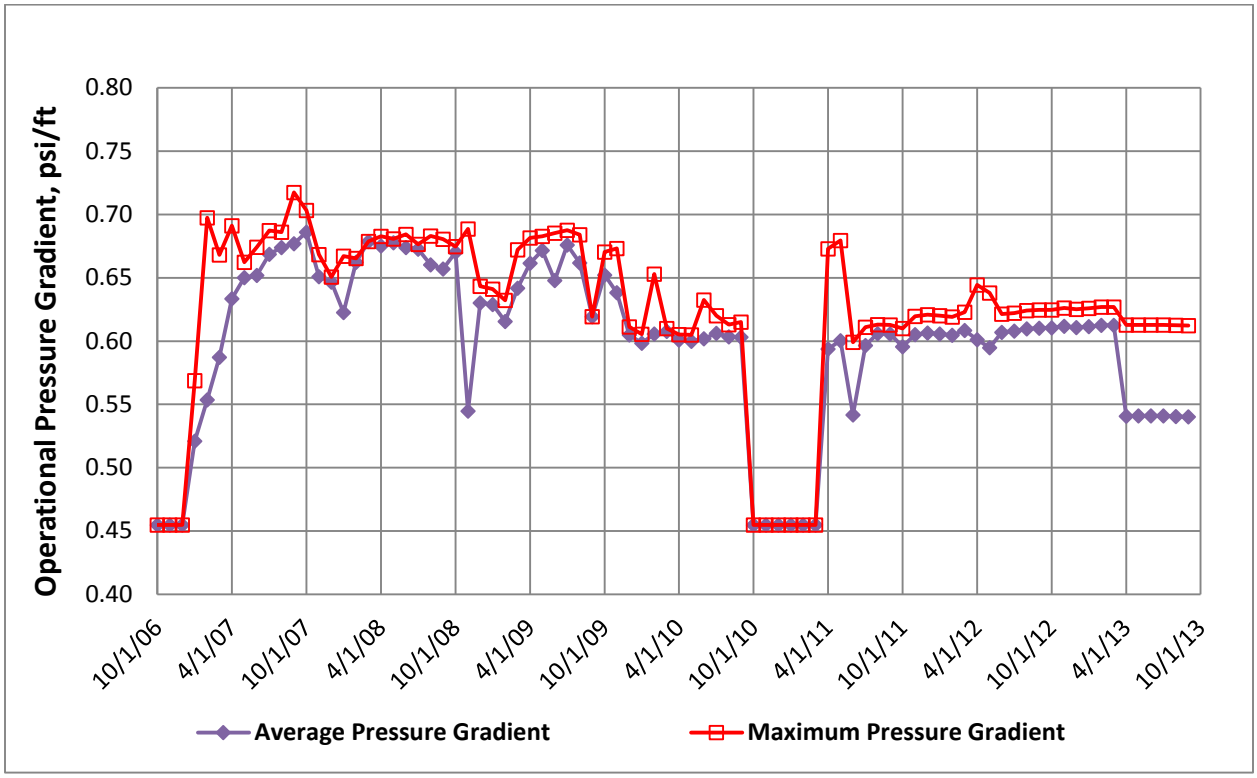


FIGURE E- 31: ROSE OPERATIONAL PRESSURE GRADIENT PLOT

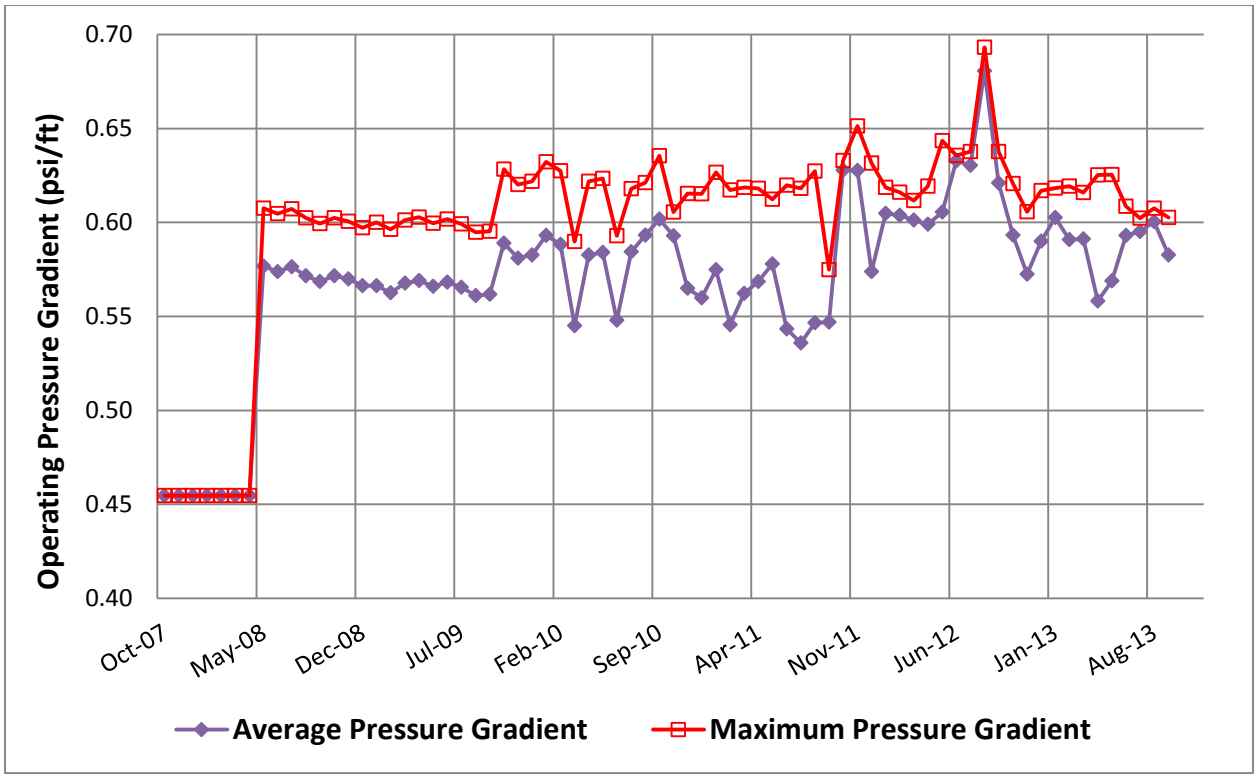


FIGURE E- 32: VORTEX OPERATIONAL PRESSURE GRADIENT PLOT

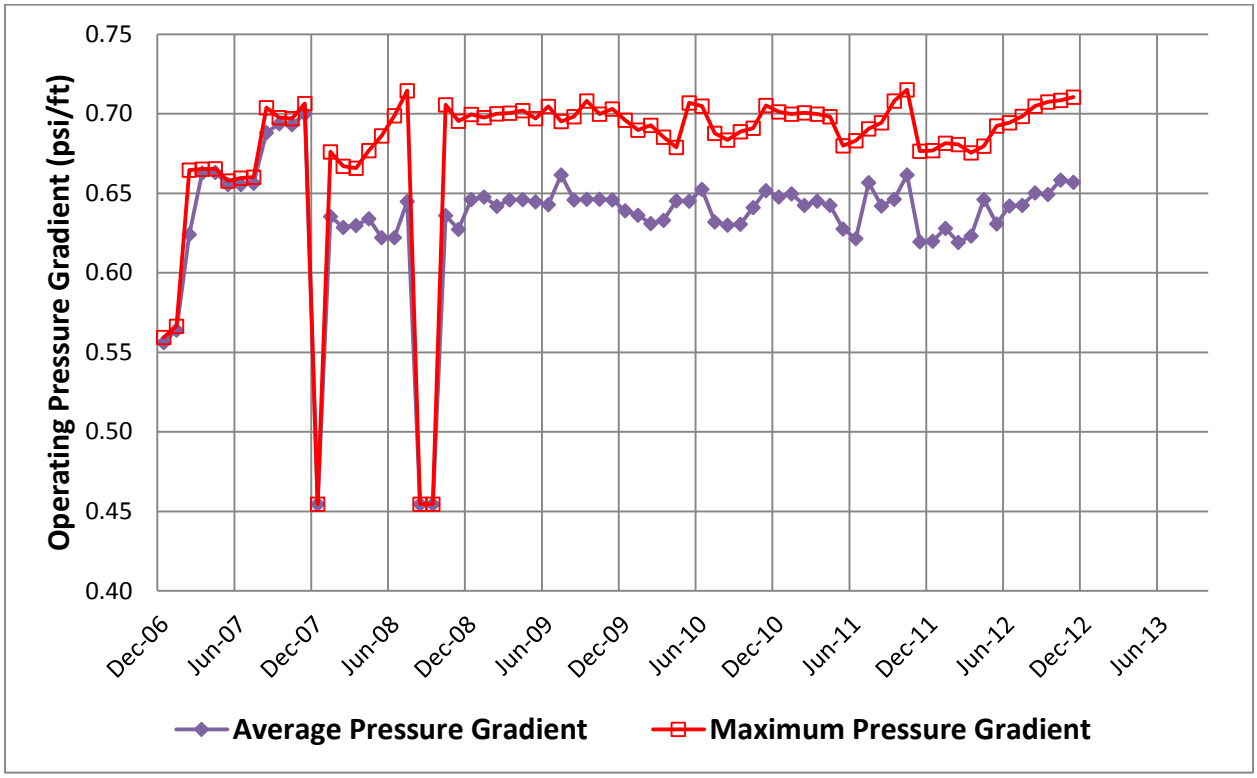


FIGURE E- 33: MANN OPERATIONAL PRESSURE GRADIENT PLOT

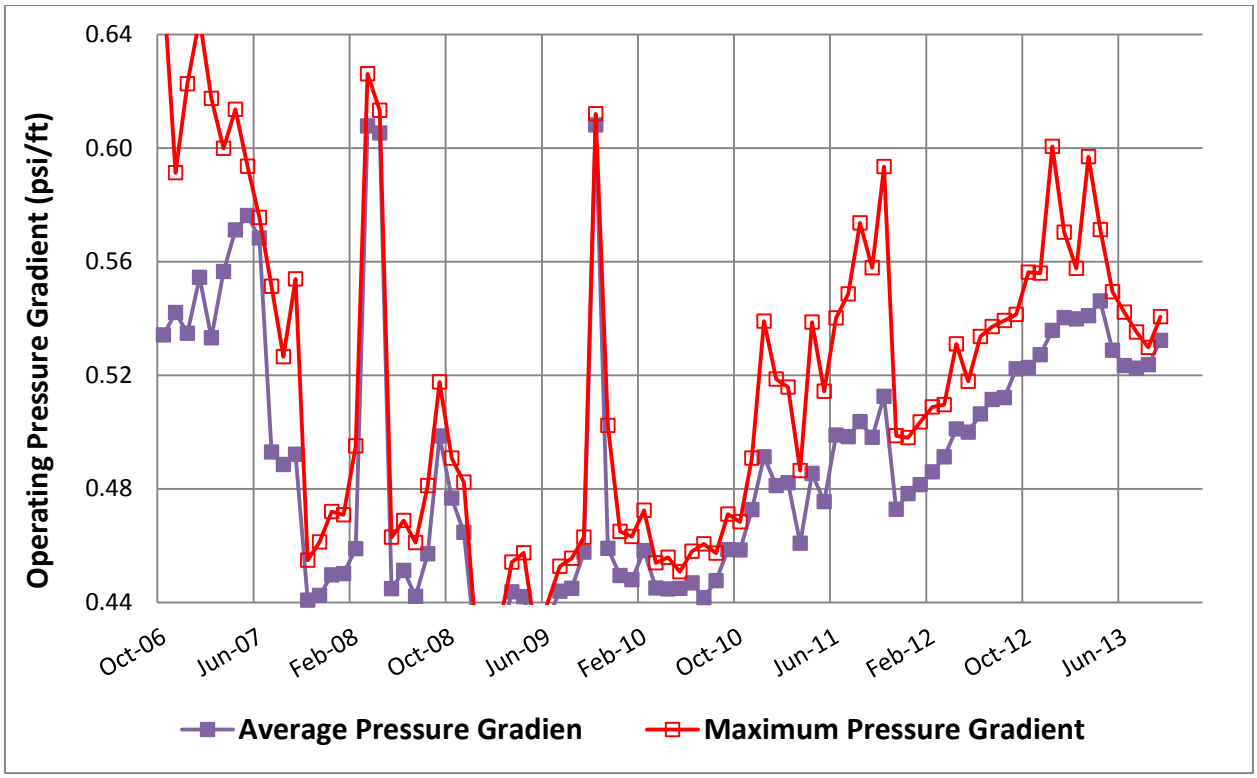


FIGURE E- 34: SPARKS DRIVE OPERATIONAL PRESSURE GRADIENT PLOT

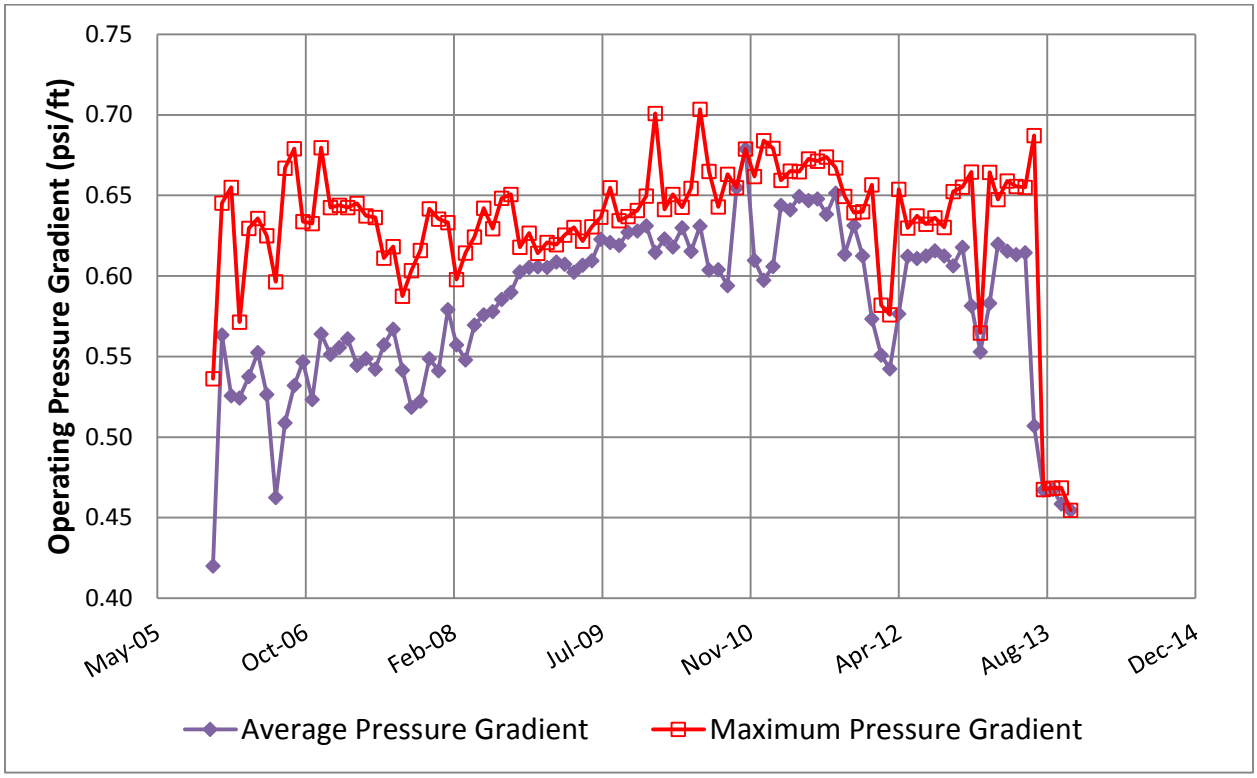


FIGURE E- 35: JOHNSON COUNTY OPERATIONAL PRESSURE GRADIENT PLOT

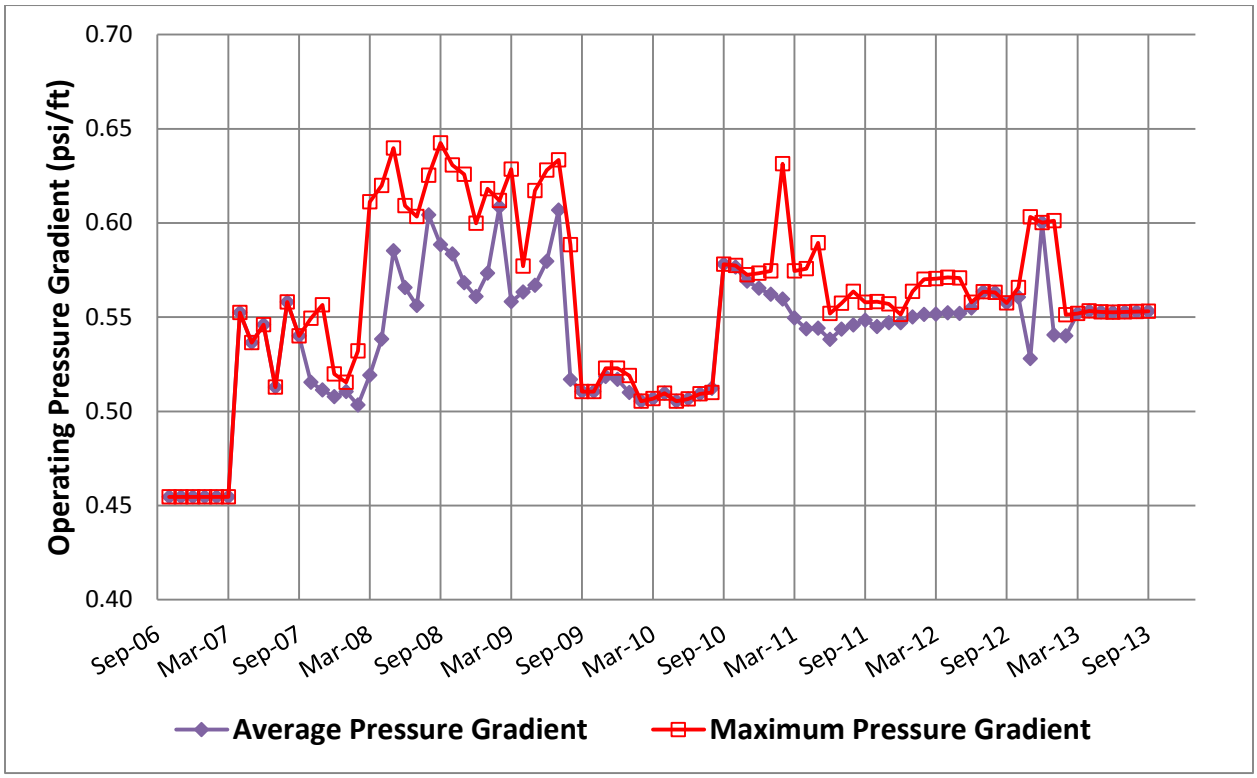


FIGURE E- 36: SOUTH CLEBURNE OPERATIONAL GRADIENT PRESSURE PLOT

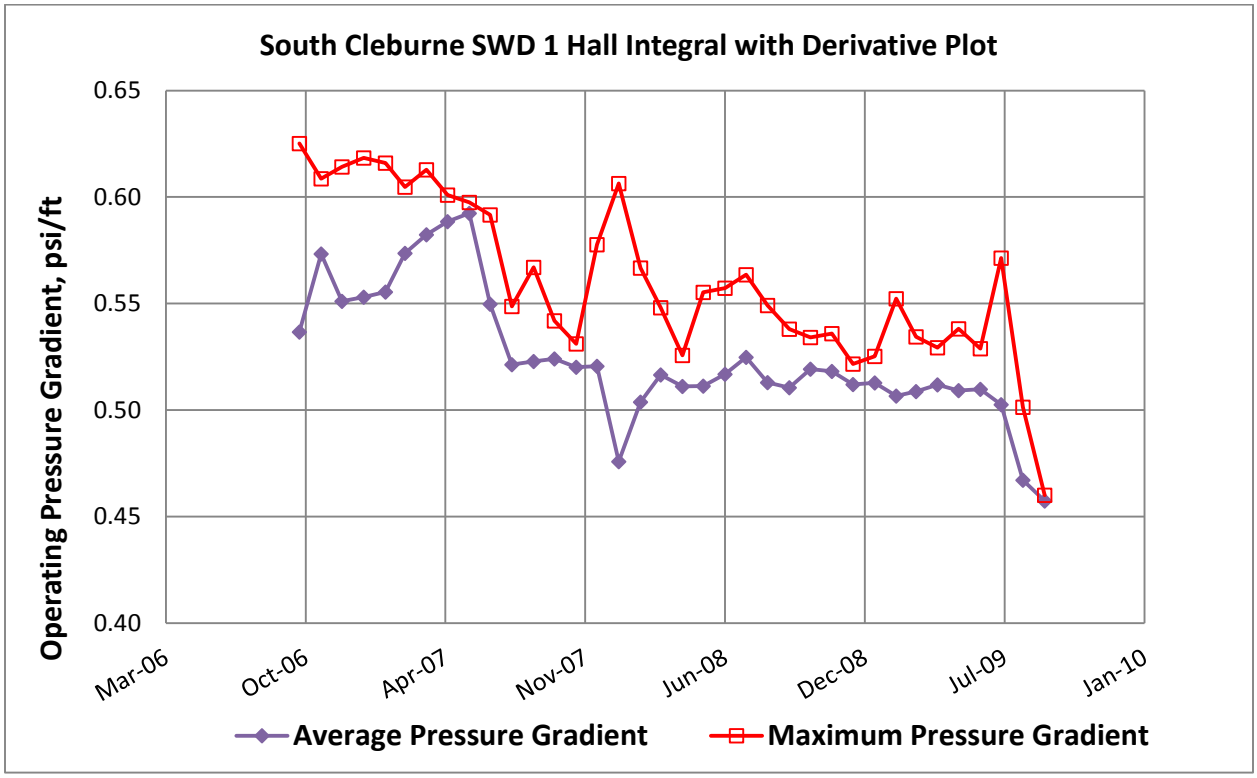


FIGURE E- 37: CLEBURNE YARD OPERATIONAL PRESSURE GRADIENT PLOT

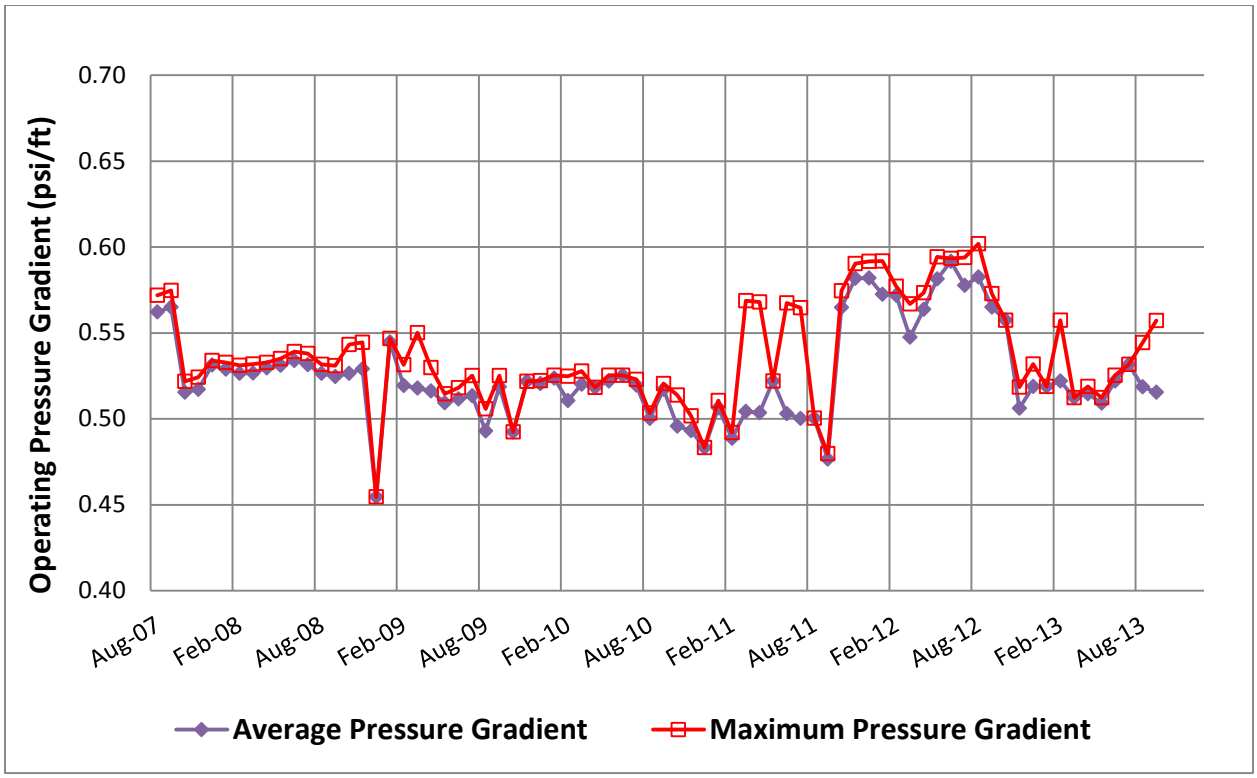


FIGURE E- 38: JOHNSON SALTY II OPERATIONAL PRESSURE PLOT

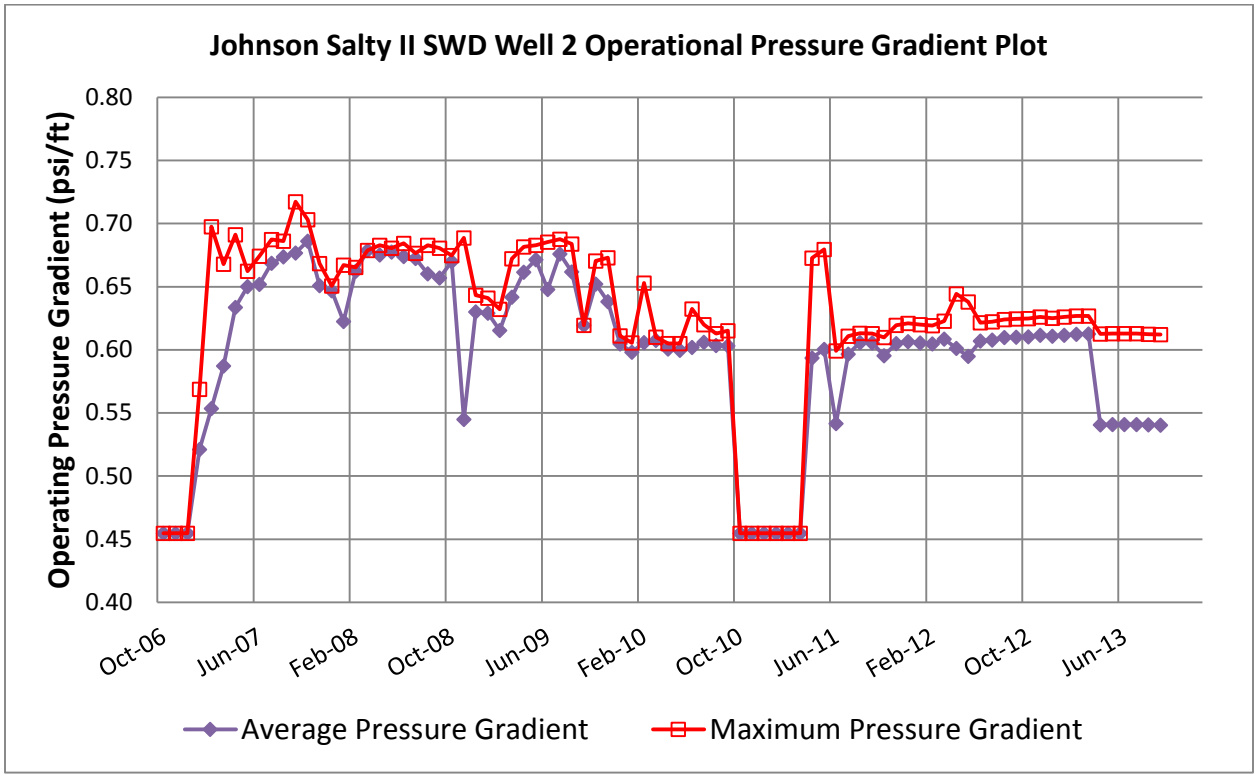


FIGURE E- 39: HANNA TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

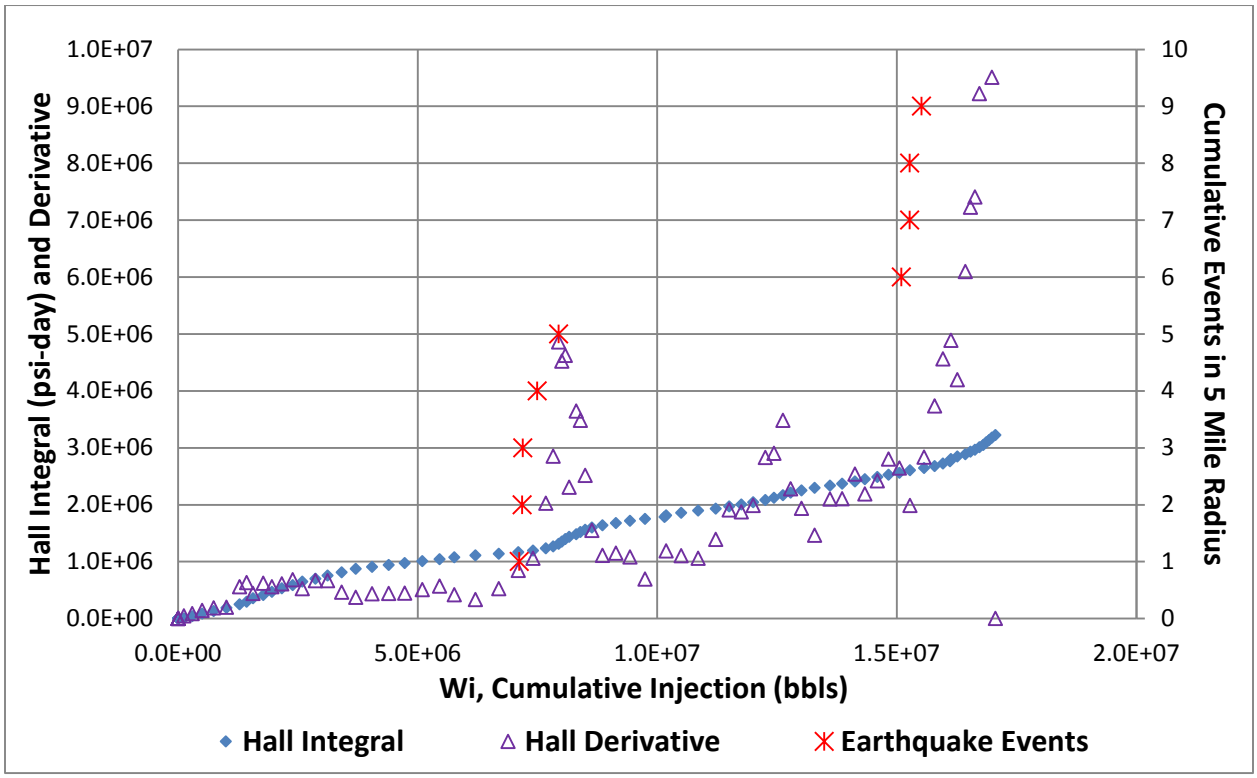


FIGURE E- 40: JOHNSON SALTY III TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

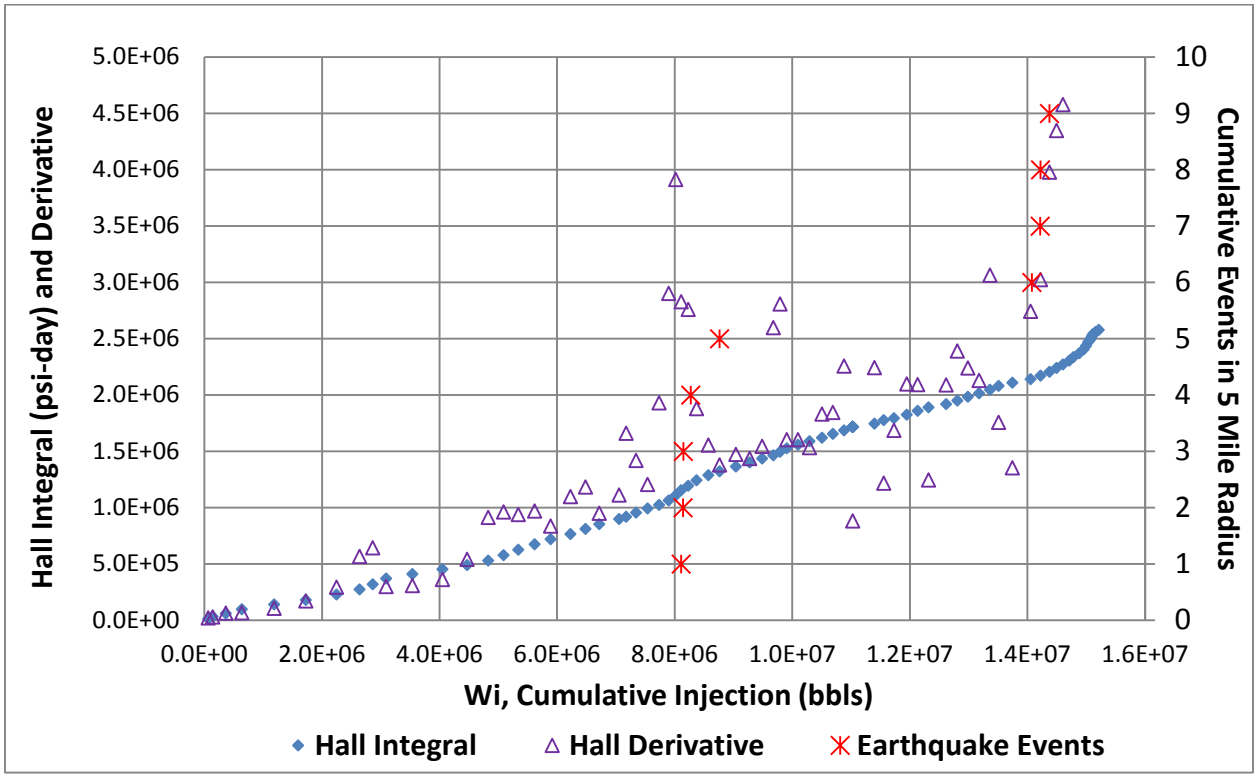


FIGURE E- 41: ROSE TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

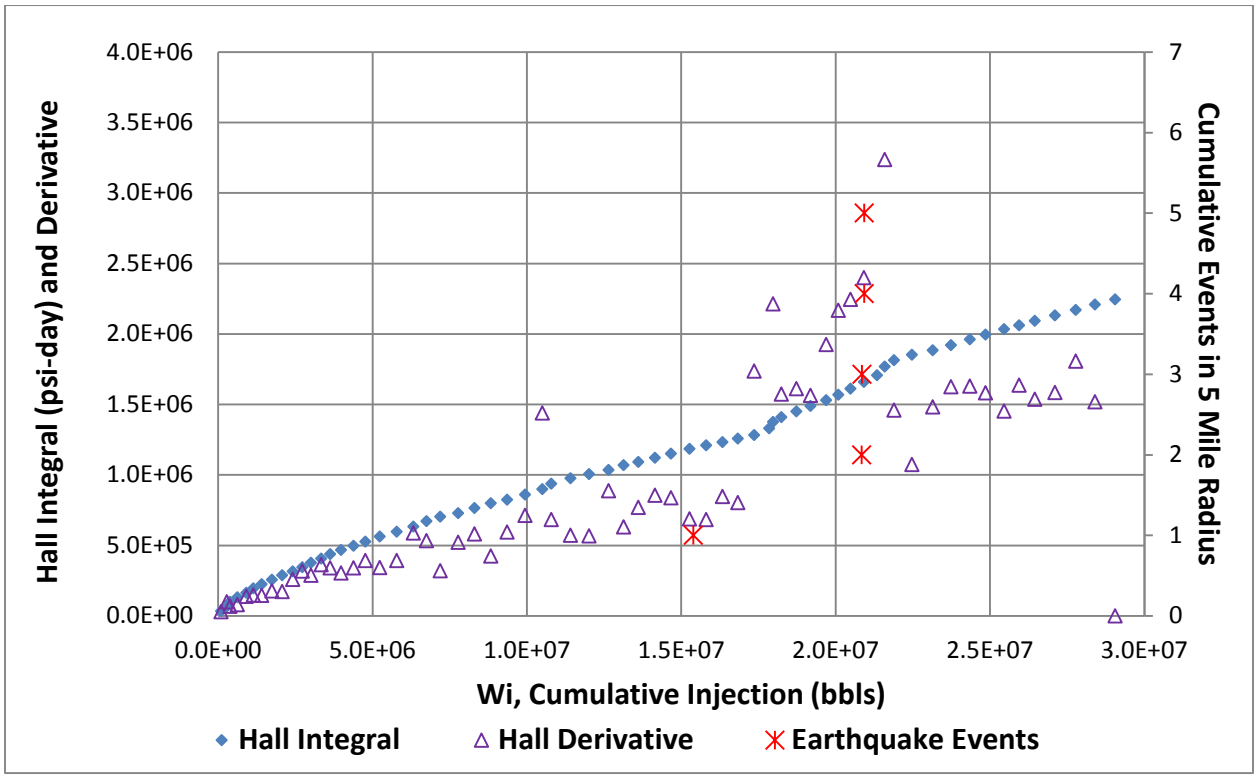


FIGURE E- 42: VORTEX TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

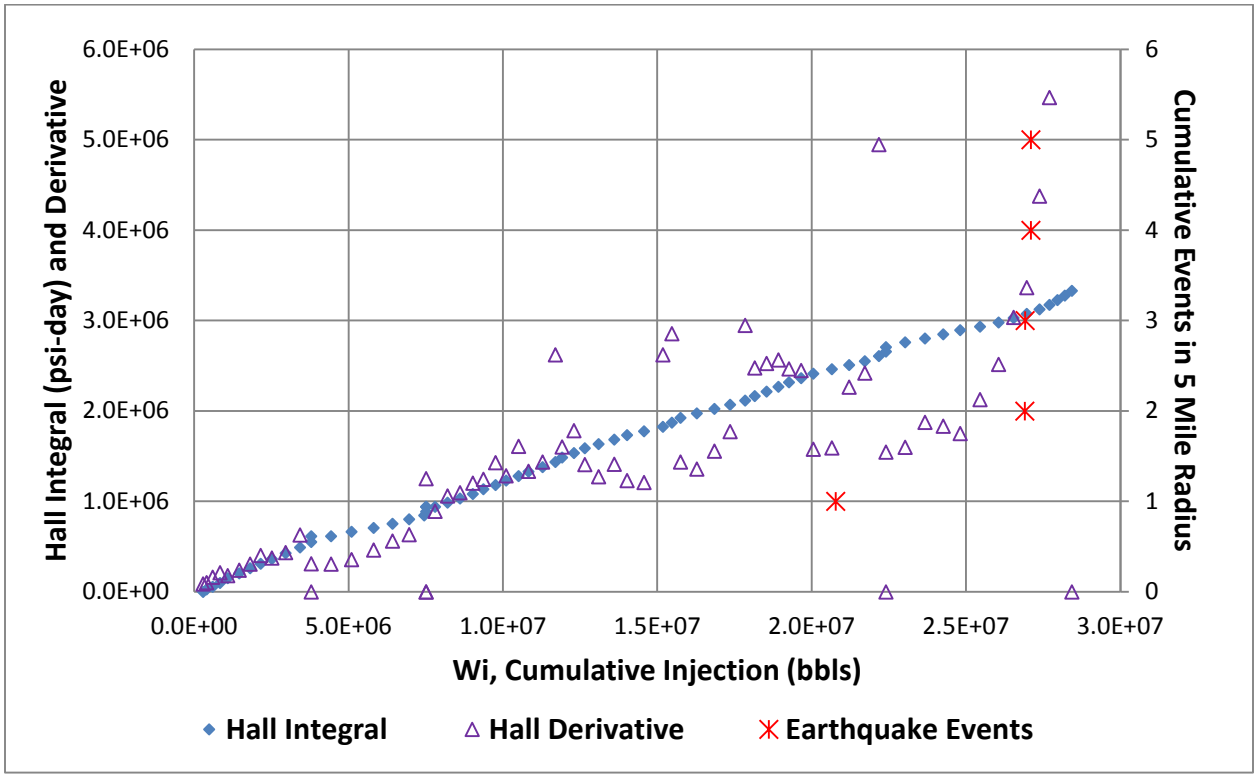


FIGURE E- 43: MANN TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

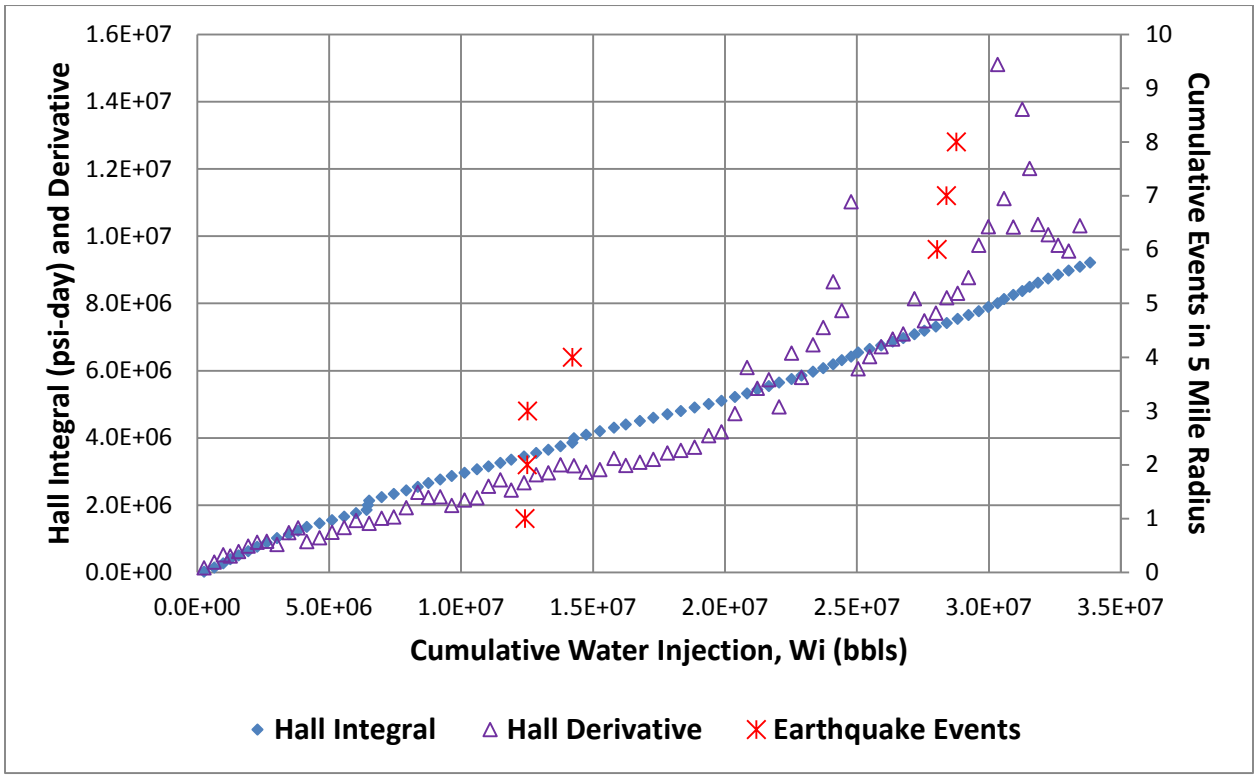


FIGURE E- 44: SPARKS DRIVE TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

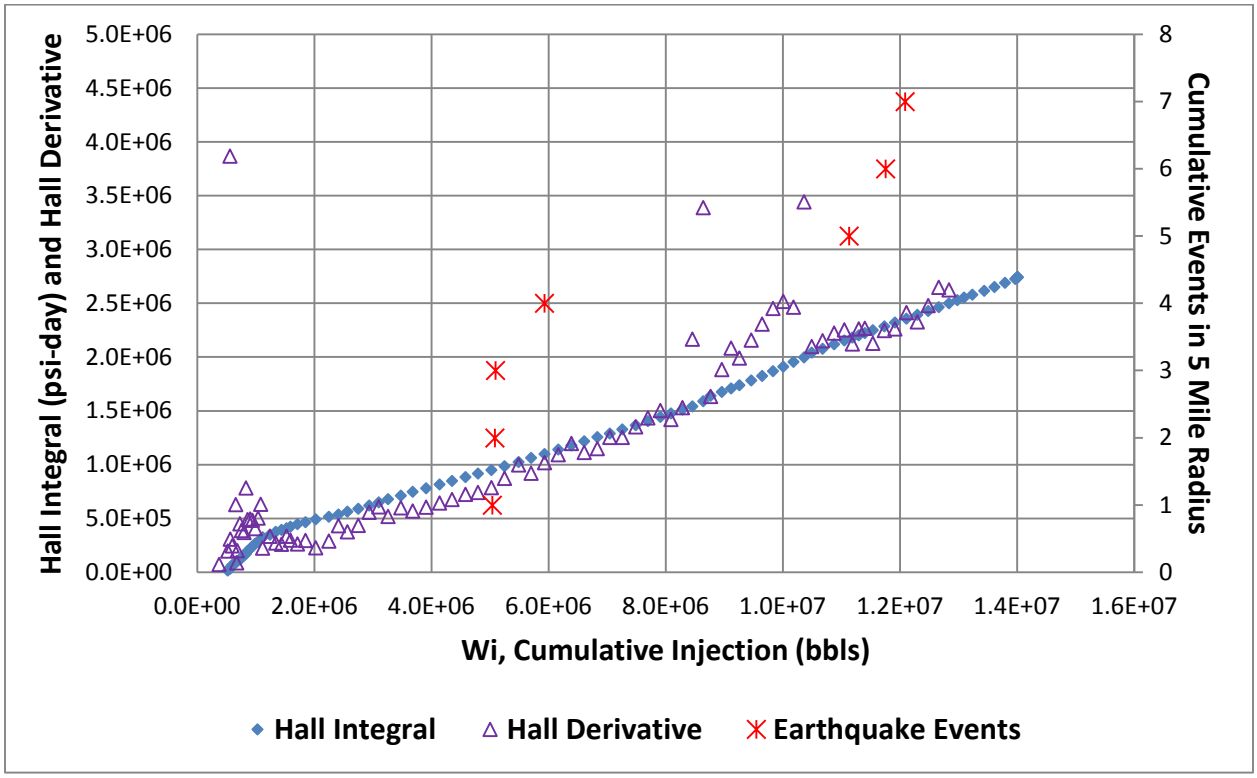


FIGURE E- 45: JOHNSON COUNTY TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

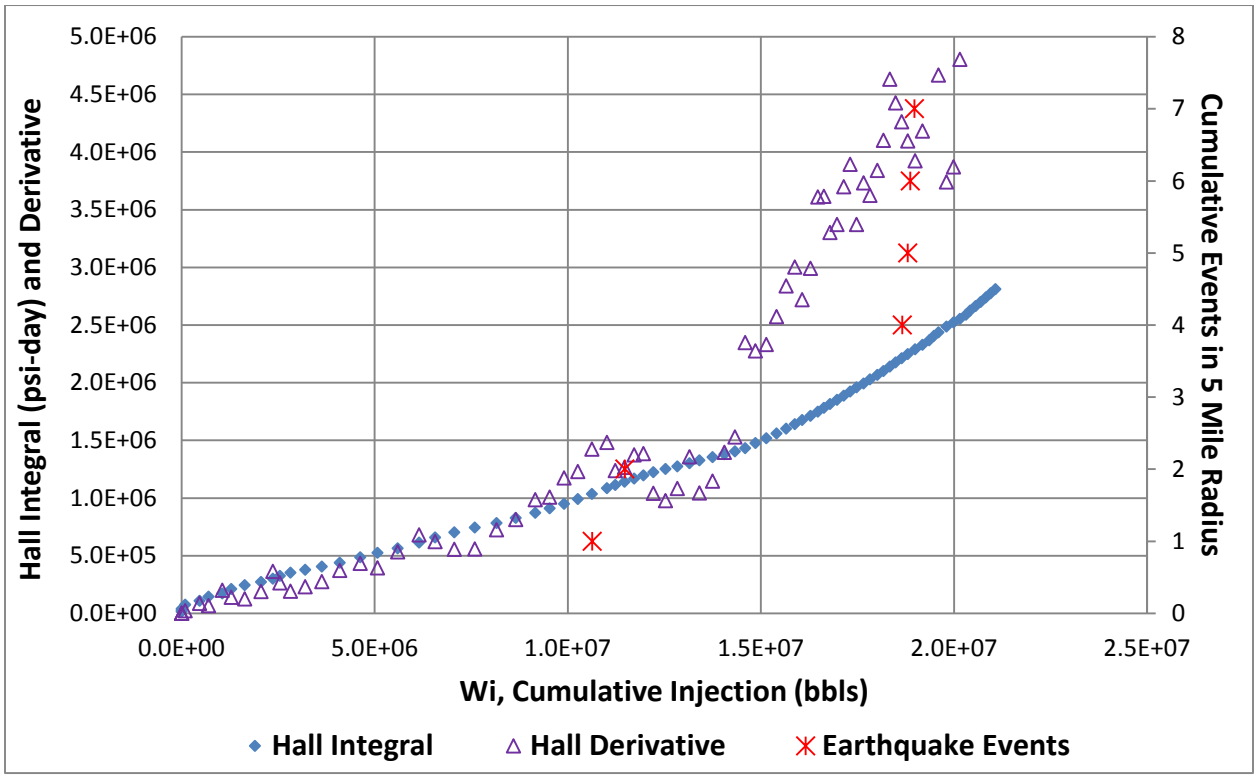


FIGURE E- 46: SOUTH CLEBURNE TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

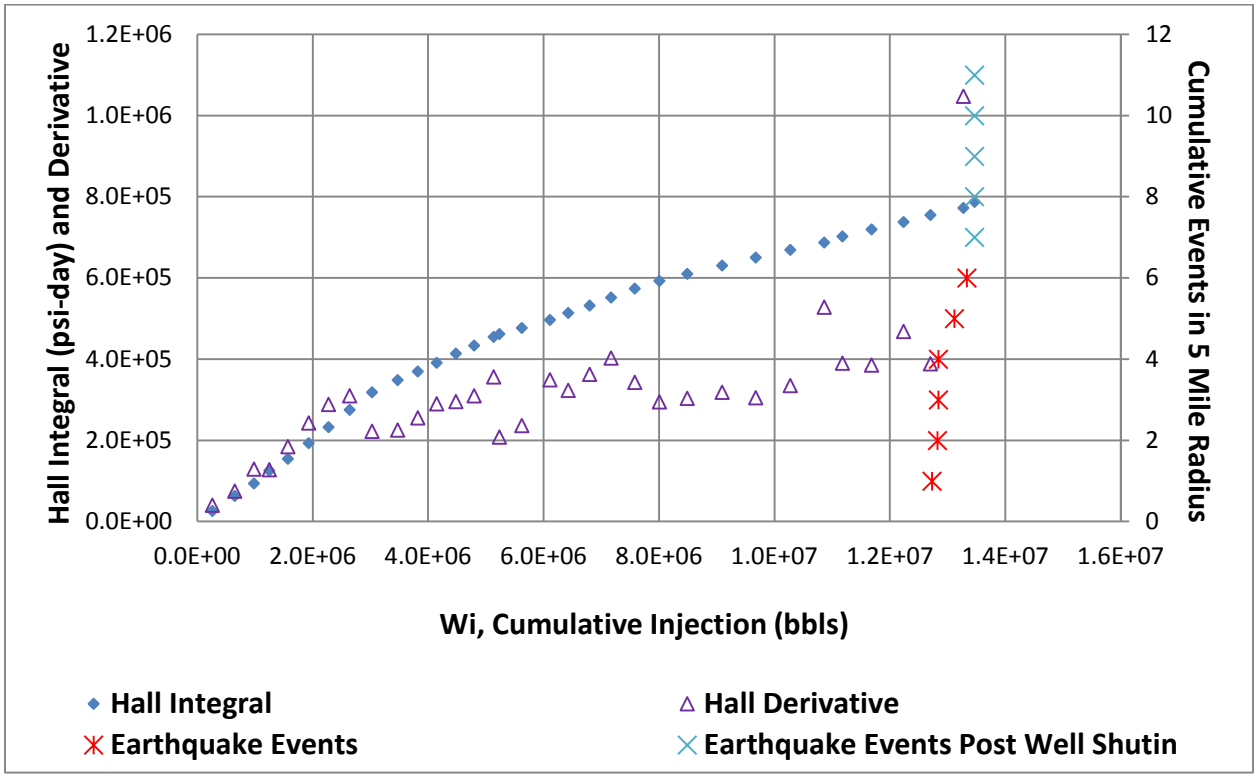


FIGURE E- 47: CLEBURN YARD TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

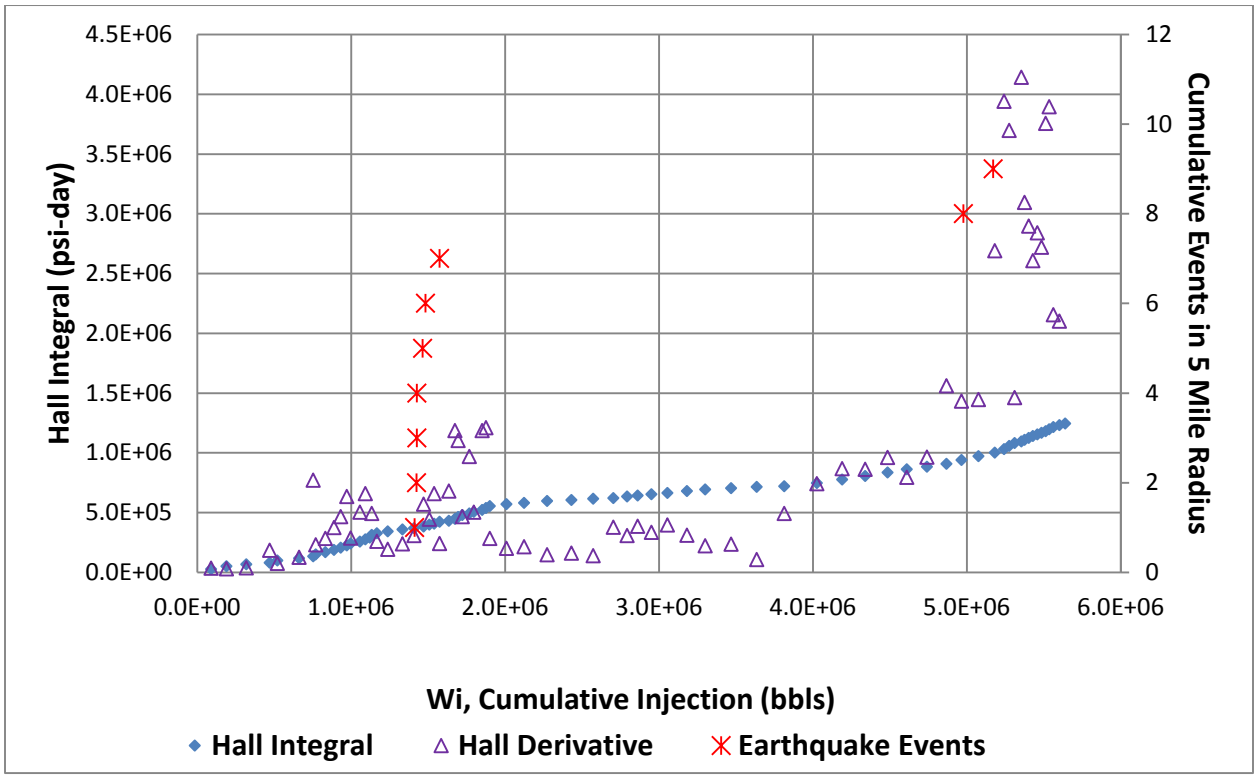


FIGURE E- 48: JOHNSON SALTY II TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

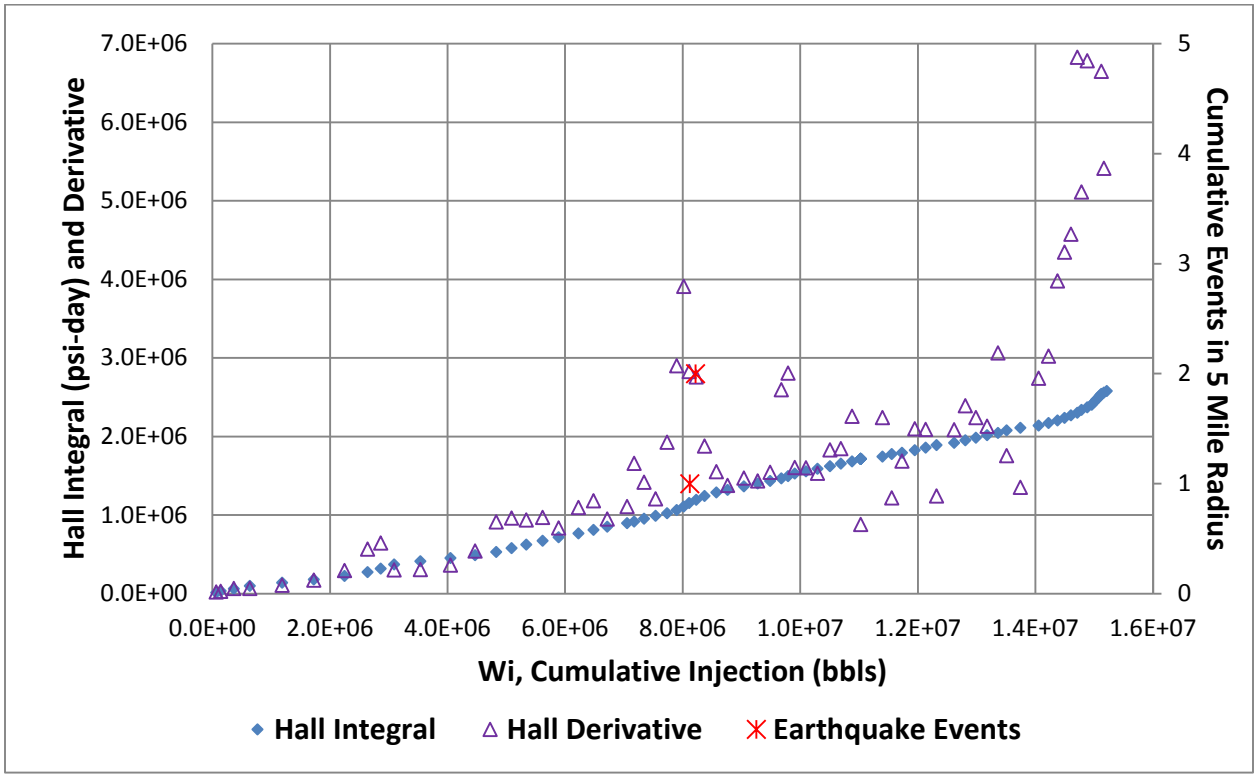


FIGURE E- 49: 2005 SPARKS FALLOFF TEST OVERVIEW PLOT

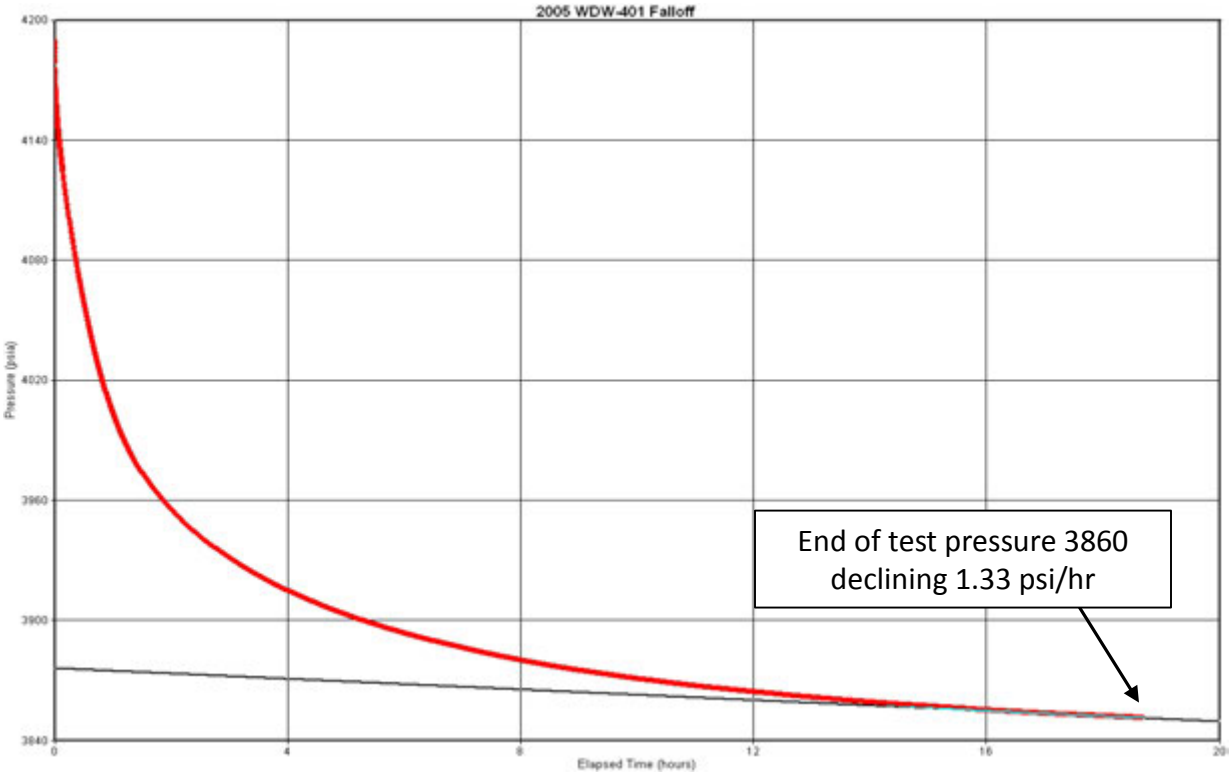


FIGURE E- 50: 2006 SPARKS FALLOFF TEST OVERVIEW PLOT

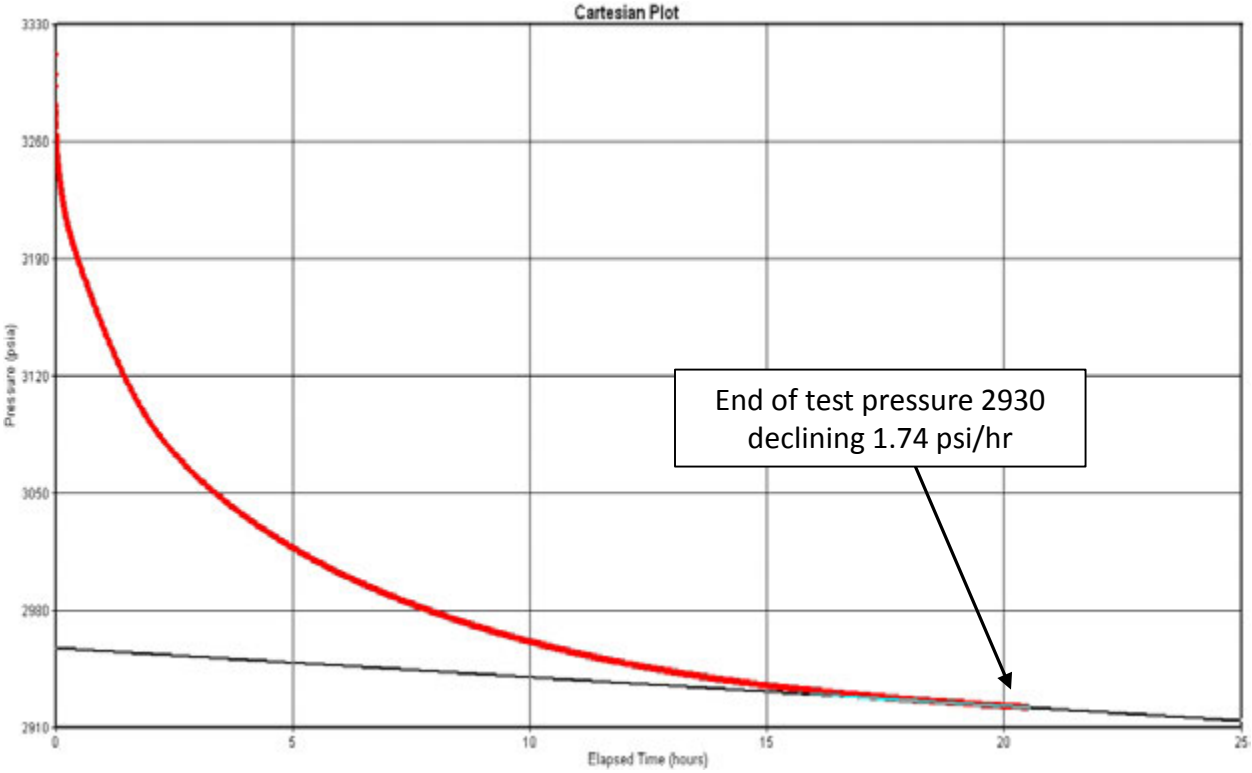


FIGURE E- 51: 2005 SPARKS FALLOFF TEST LOG-LOG PLOT

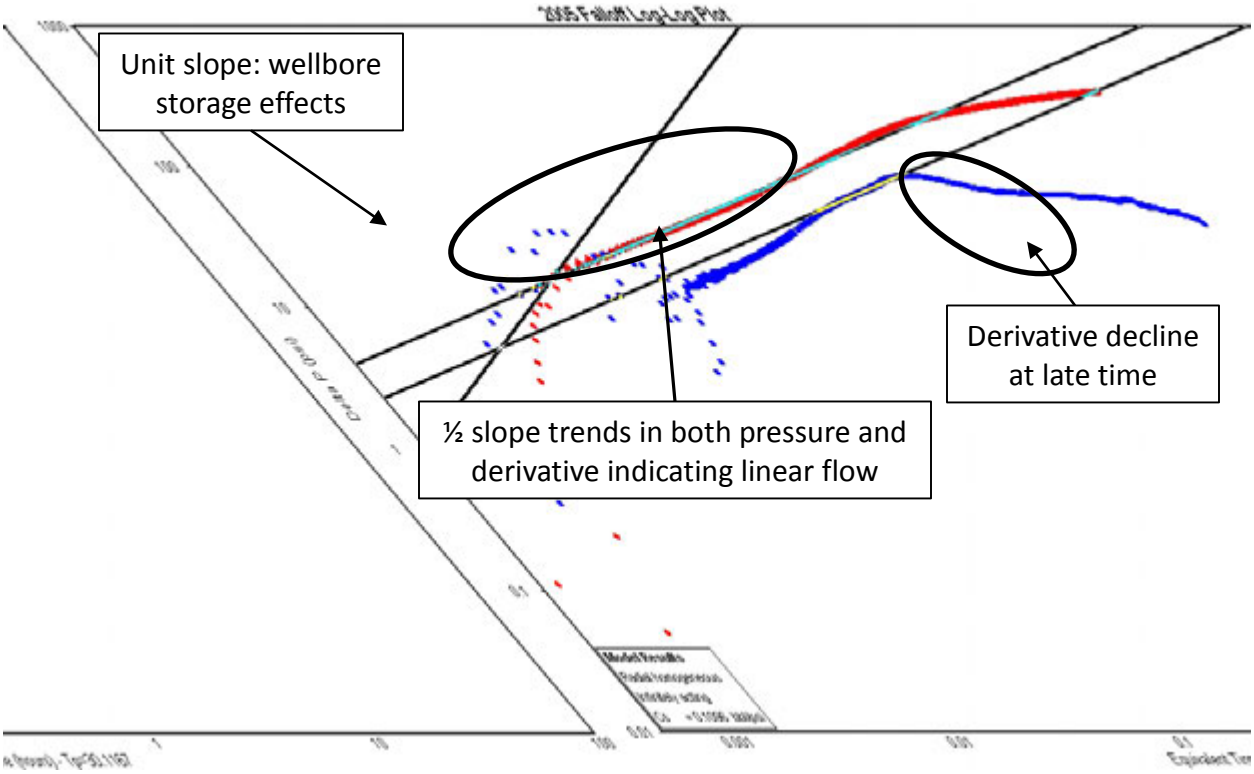


FIGURE E- 52: 2006 SPARKS FALLOFF TEST LOG-LOG PLOT

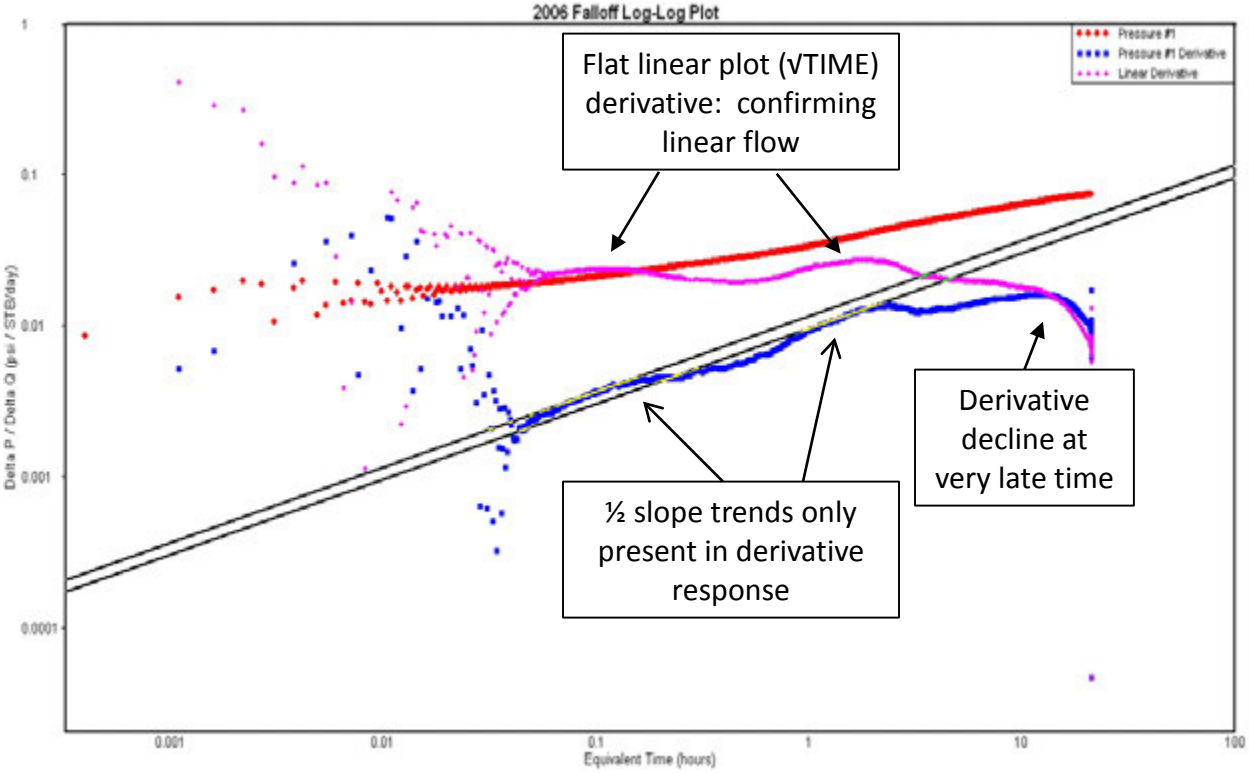


FIGURE E- 53: 2005 SPARKS TYPE CURVE MATCH

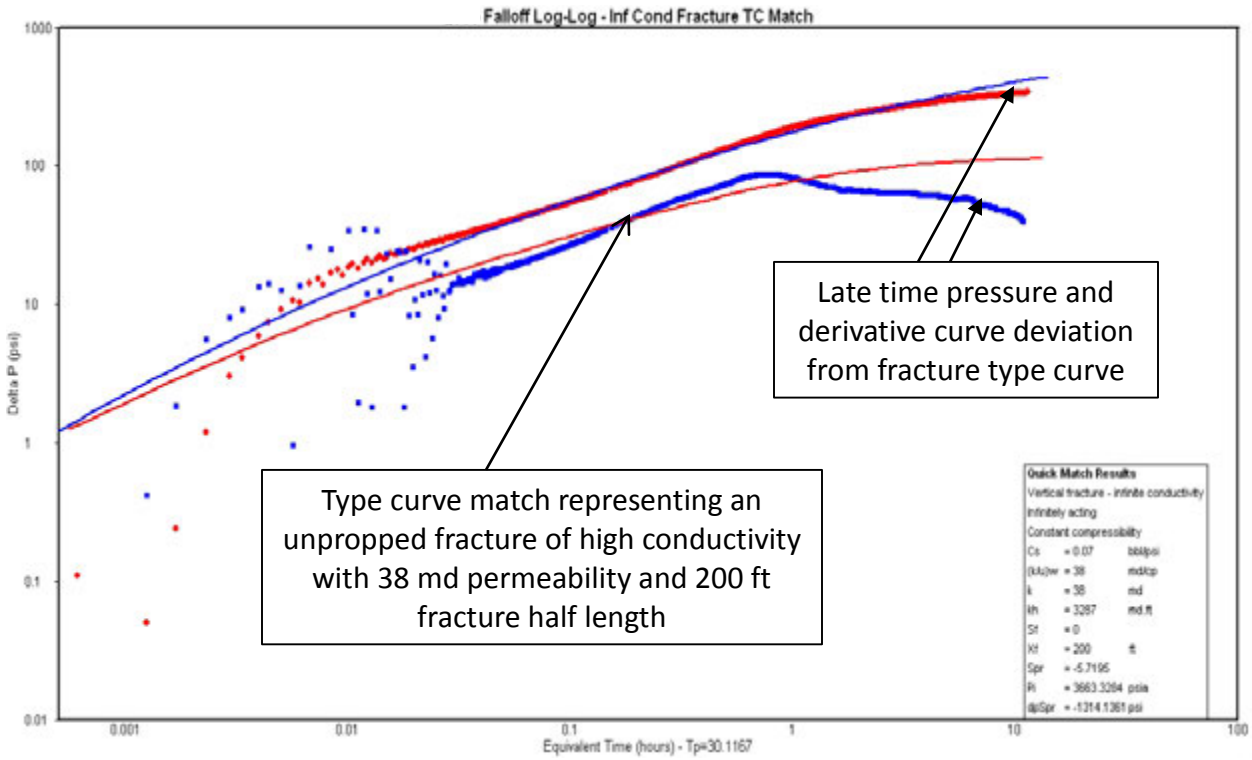


FIGURE E- 54: 2006 SPARKS TYPE CURVE MATCH

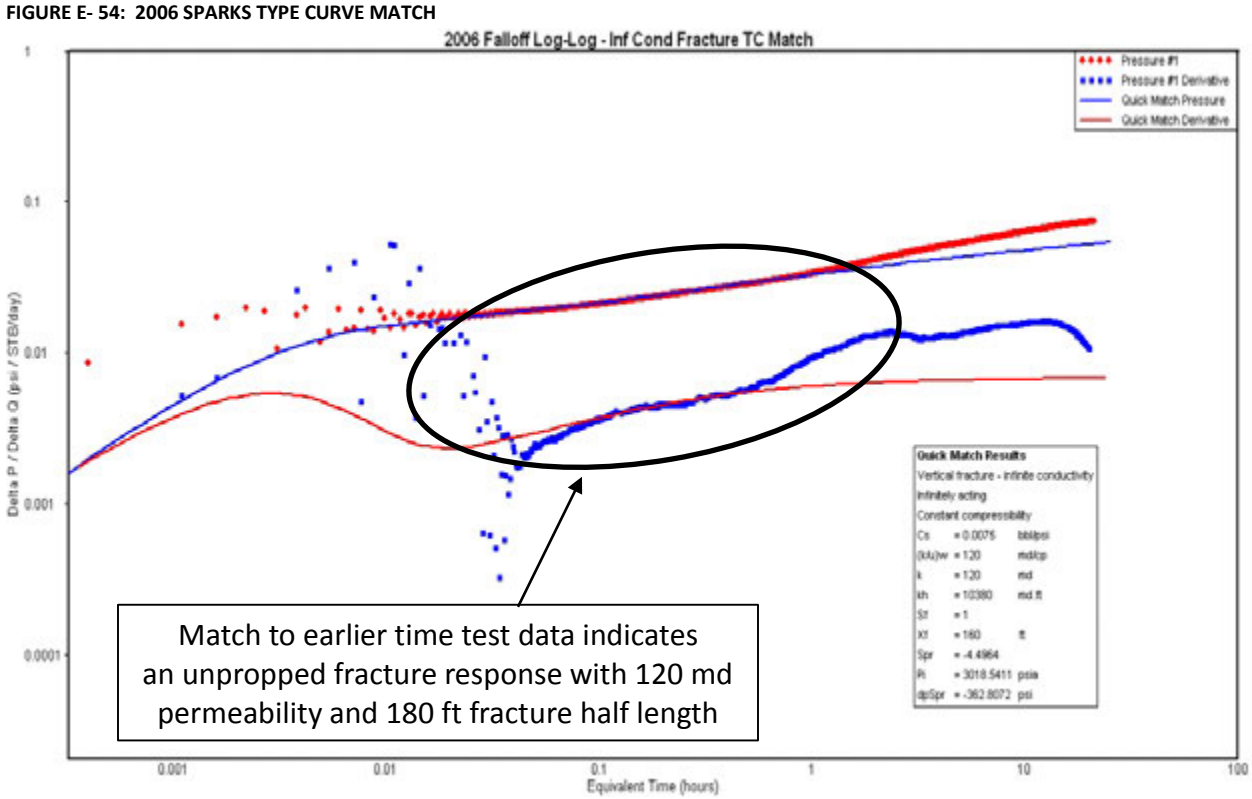


FIGURE E- 55: 2006 SPARKS TYPE CURVE MATCH OF LATE TIME DATA

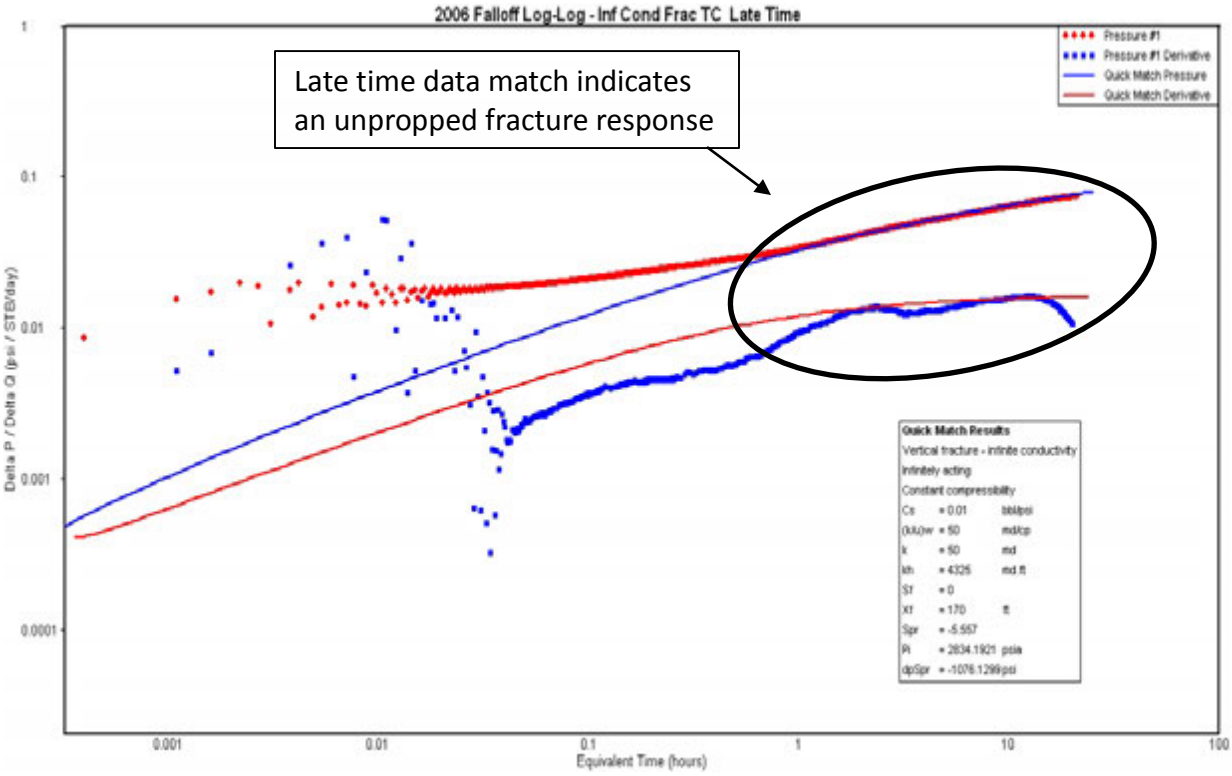


FIGURE E- 56: 2008 SPARKS FALLOFF TEST OVERVIEW PLOT

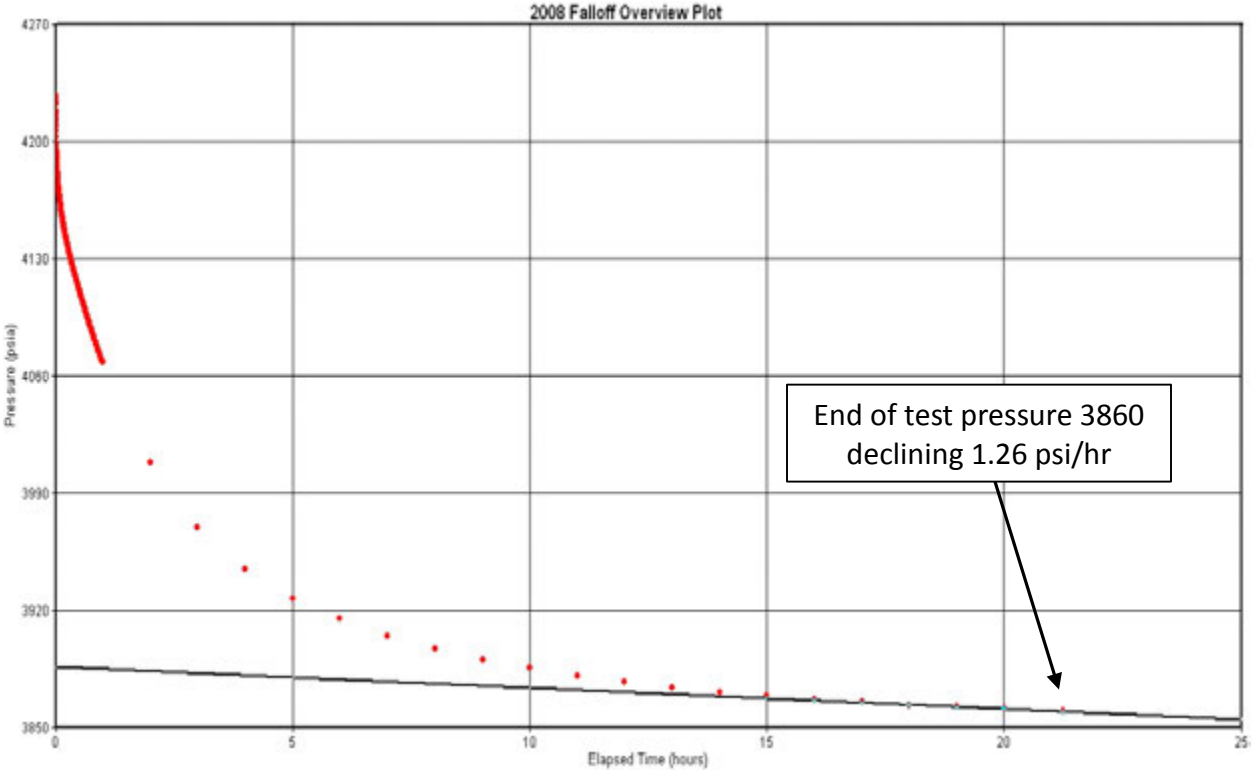


FIGURE E- 57: 2008 SPARKS LOG-LOG PLOT

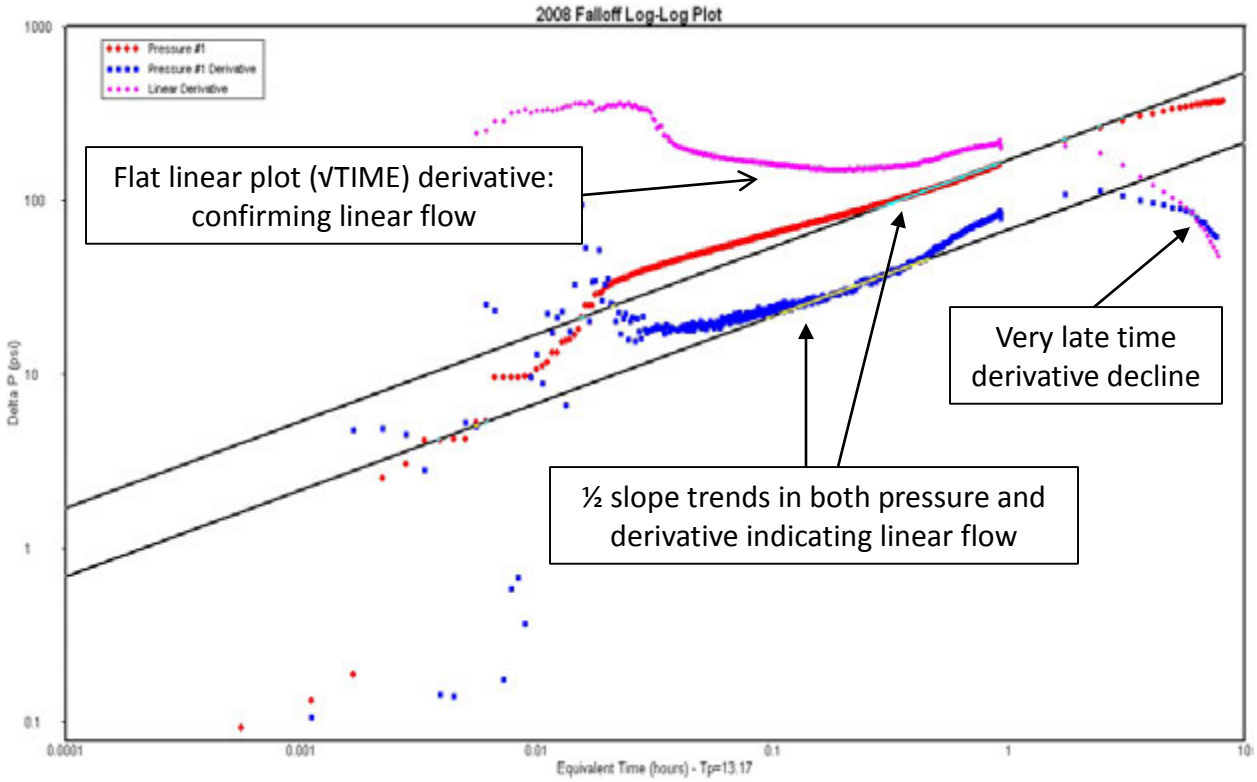


FIGURE E- 58: 2008 SPARKS TYPE CURVE MATCH – HOMOGENEOUS MODEL

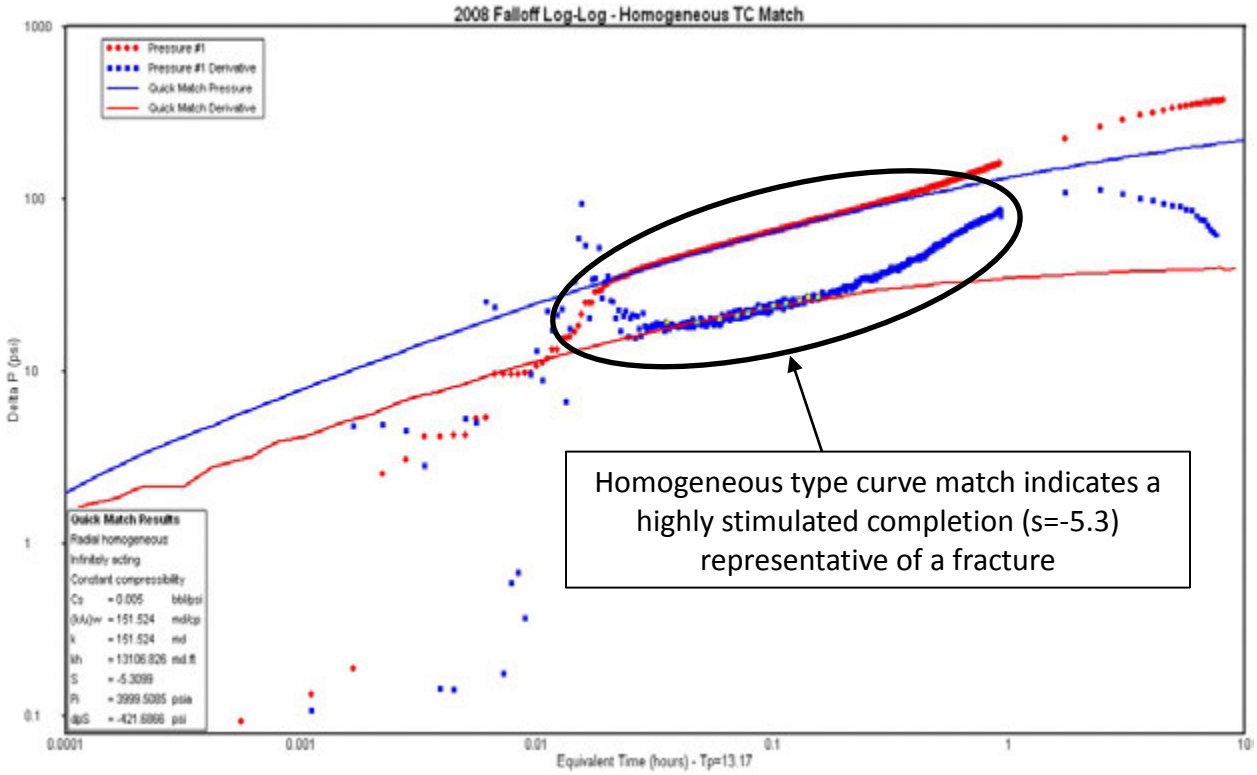


FIGURE E- 59: 2008 SPARKS TYPE CURVE MATCH

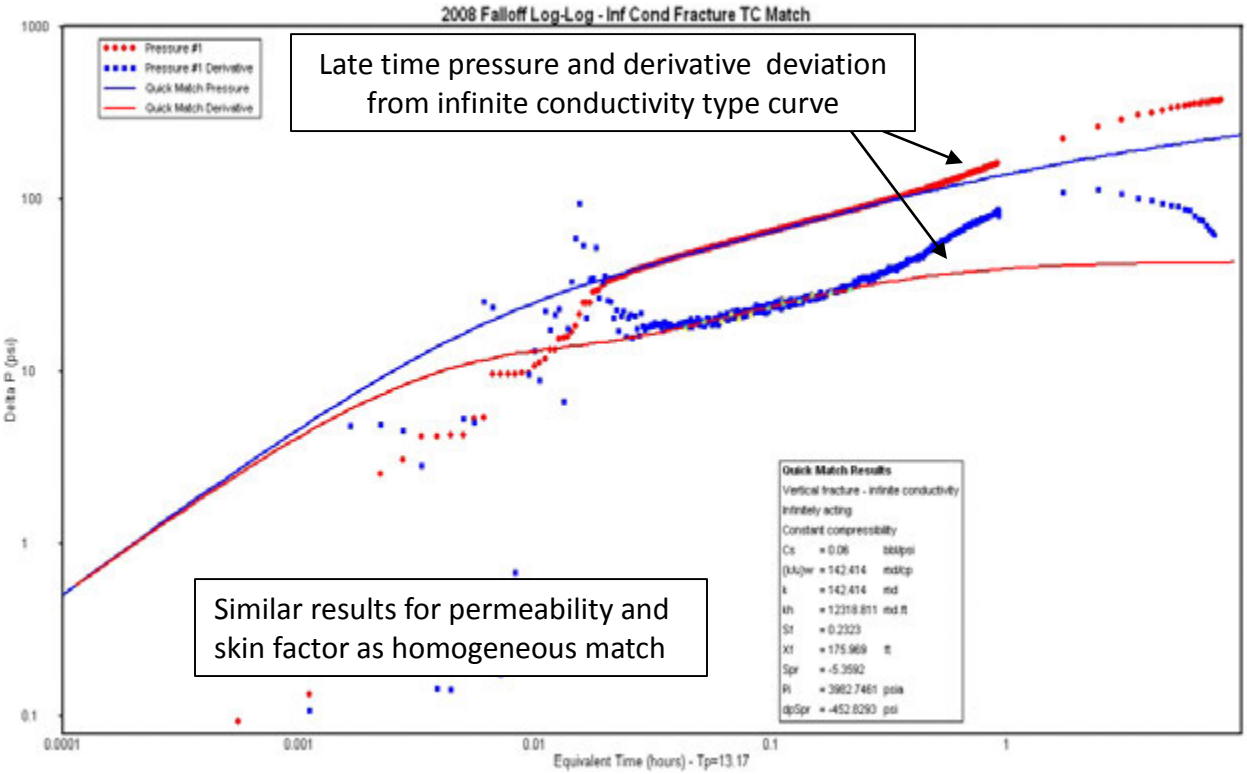


FIGURE E- 60: 2009 SPARKS FALLOFF TEST OVERVIEW PLOT

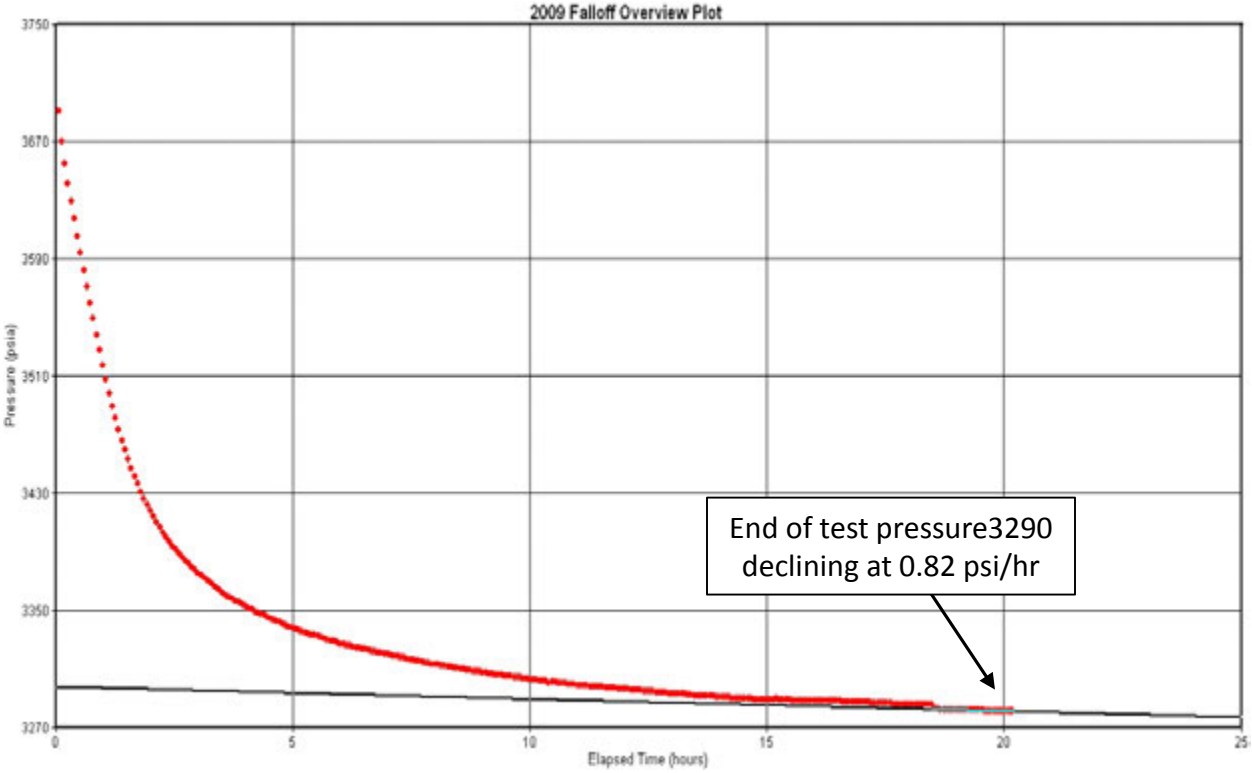


FIGURE E- 61: 2009 SPARKS LOG-LOG PLOT AND TYPE CURVE MATCH

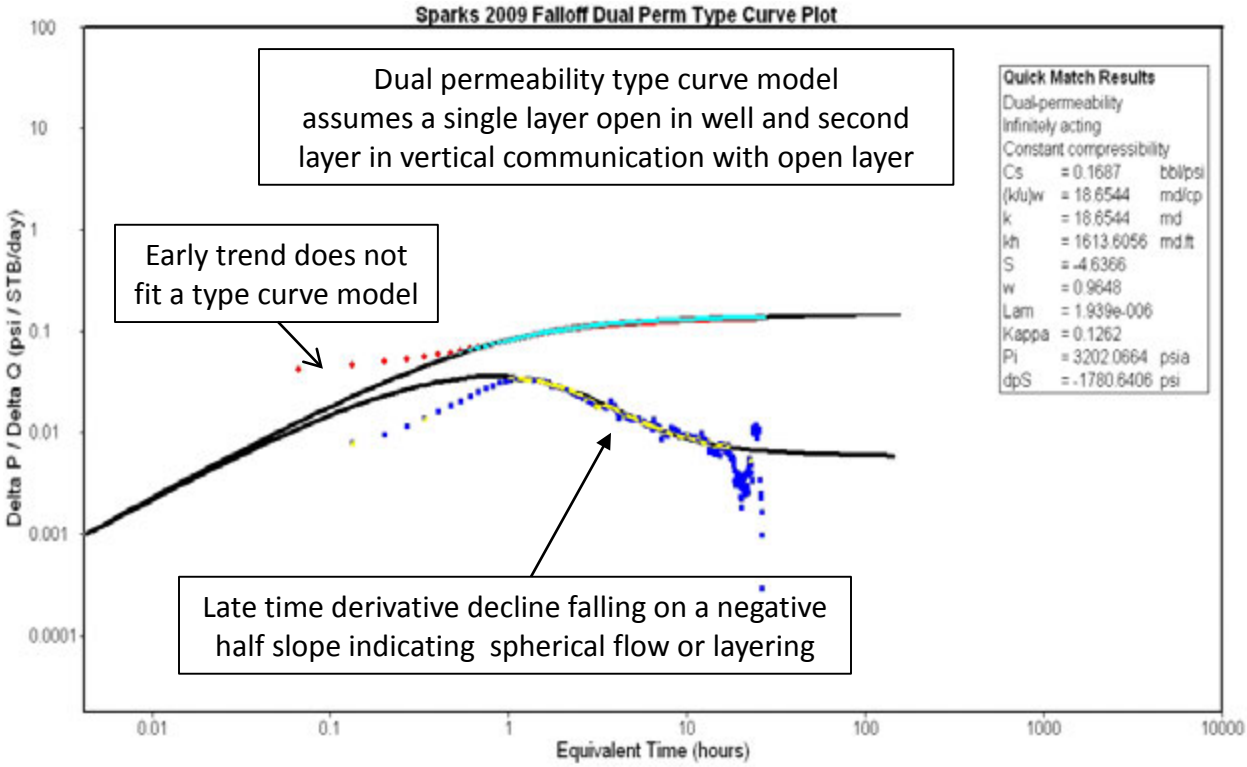


FIGURE E- 62: 2010 SPARKS FALLOFF TEST OVERVIEW PLOT

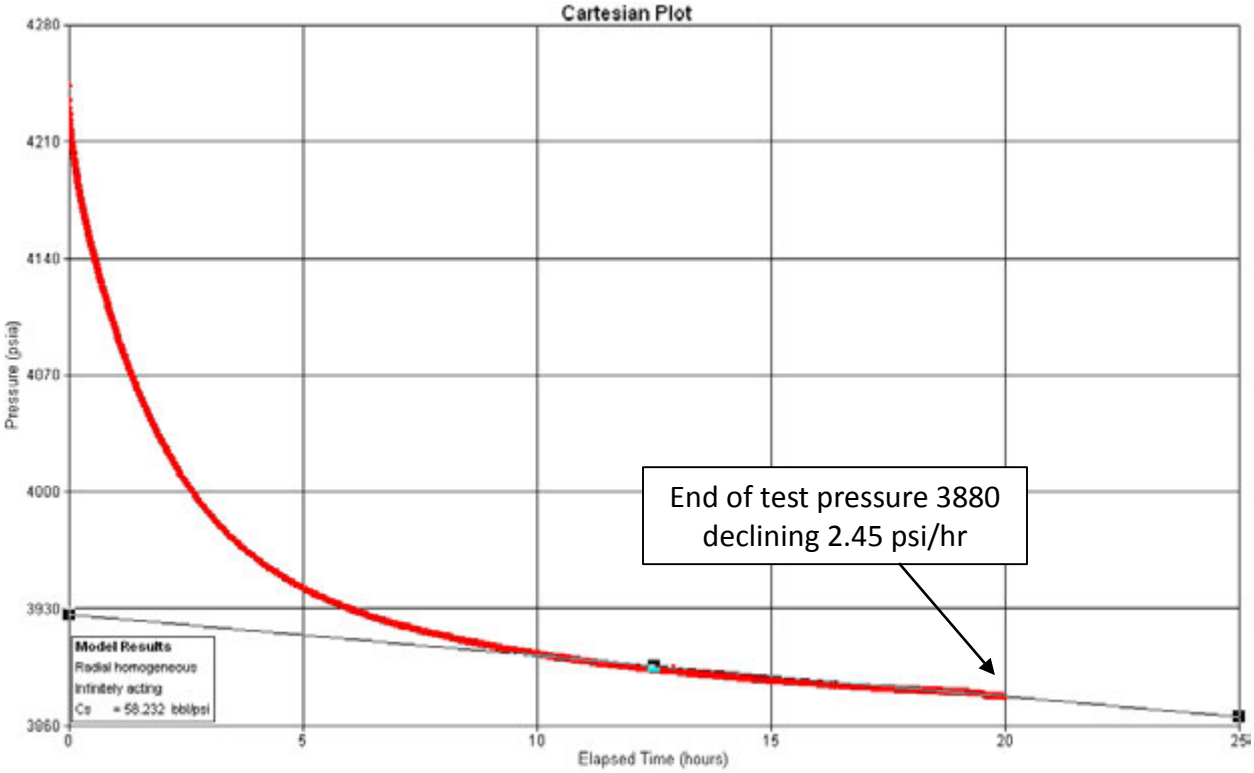


FIGURE E- 63: 2010 SPARKS LOG-LOG PLOT AND TYPE CURVE MATCH

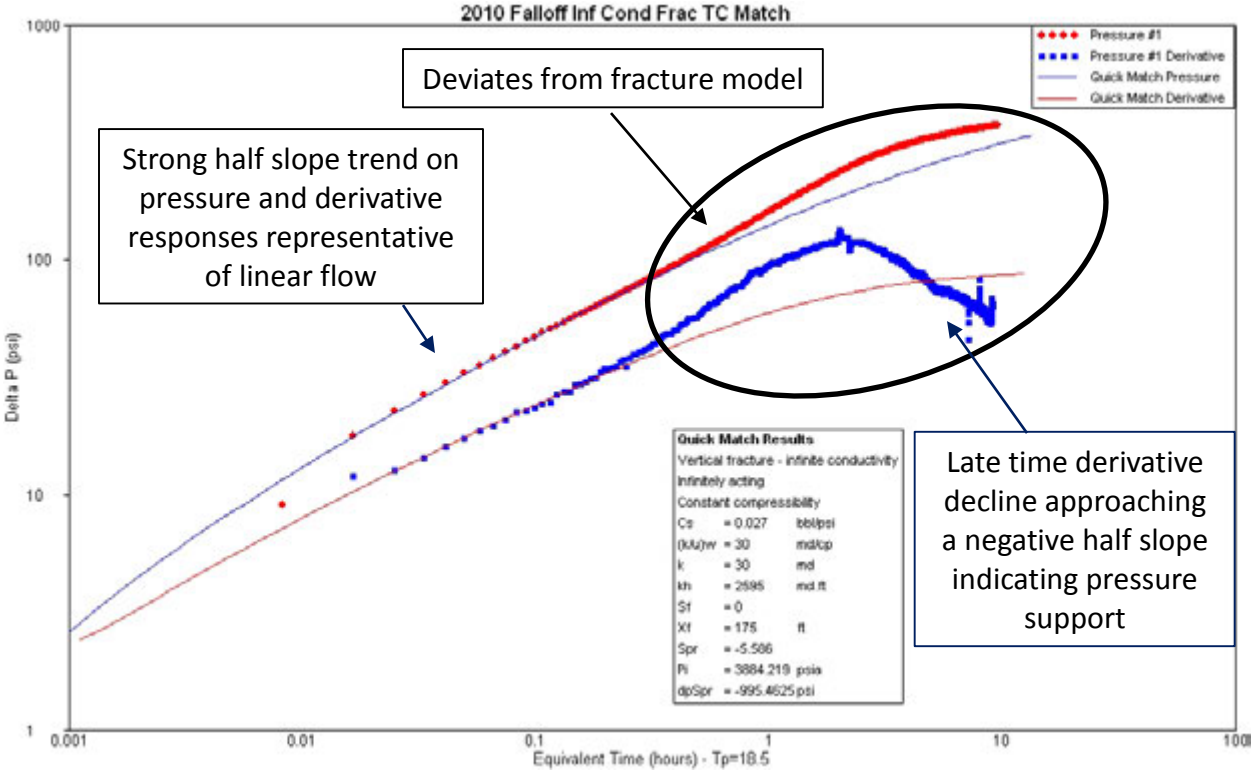


FIGURE E- 64: 2010 SPARKS TYPE CURVE MATCH OF LATE TIME DATA

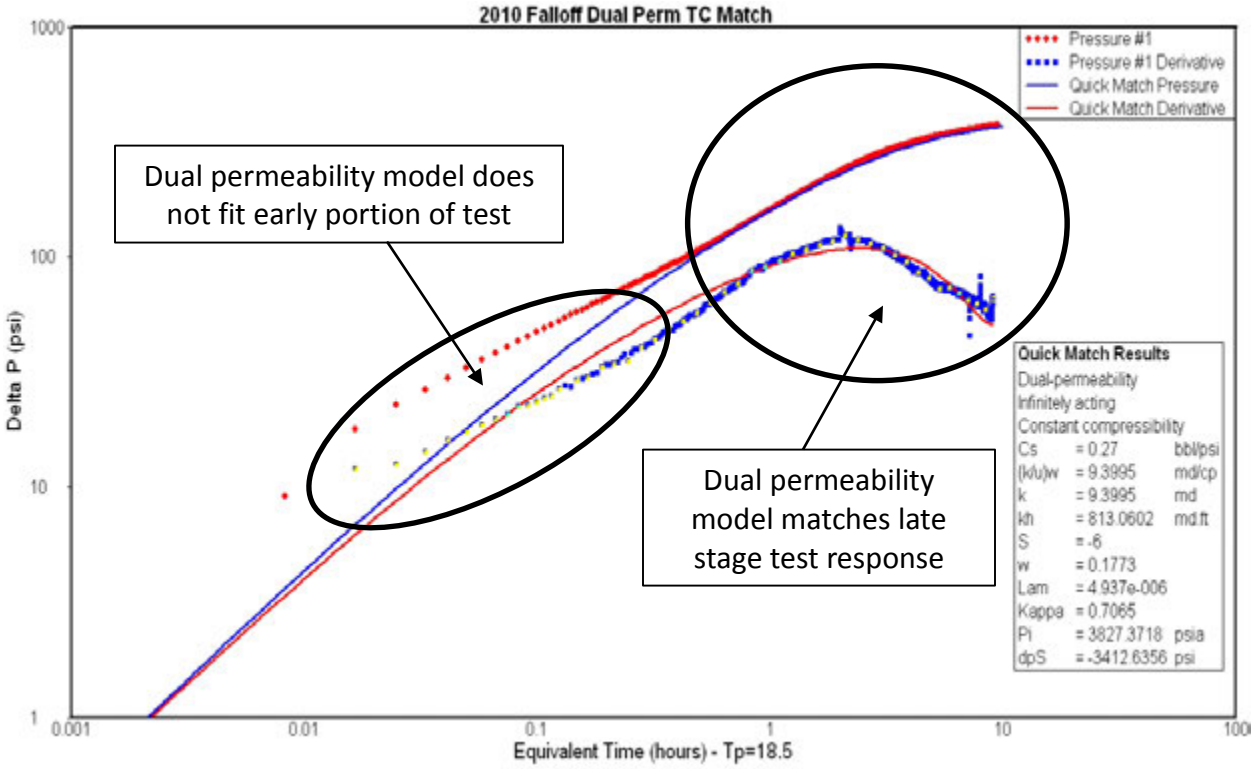


FIGURE E- 65: 2011 SPARKS FALLOFF TEST OVERVIEW PLOT

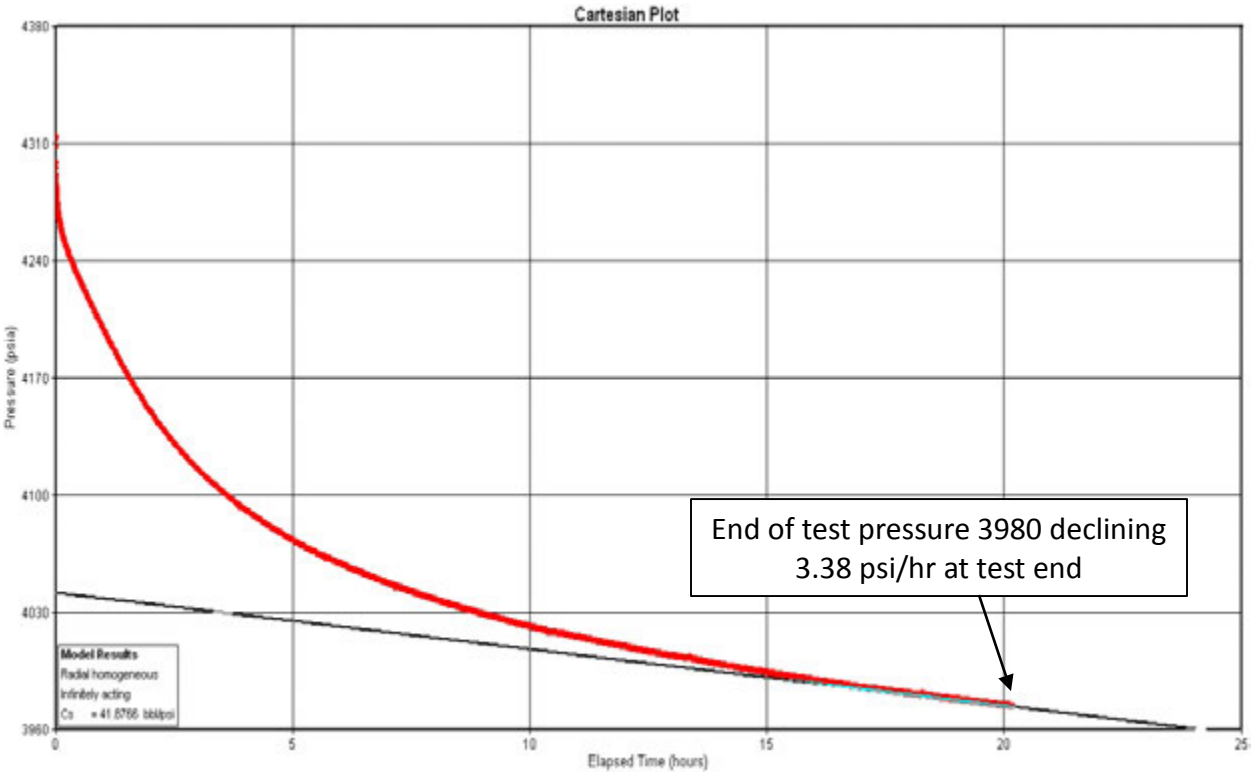
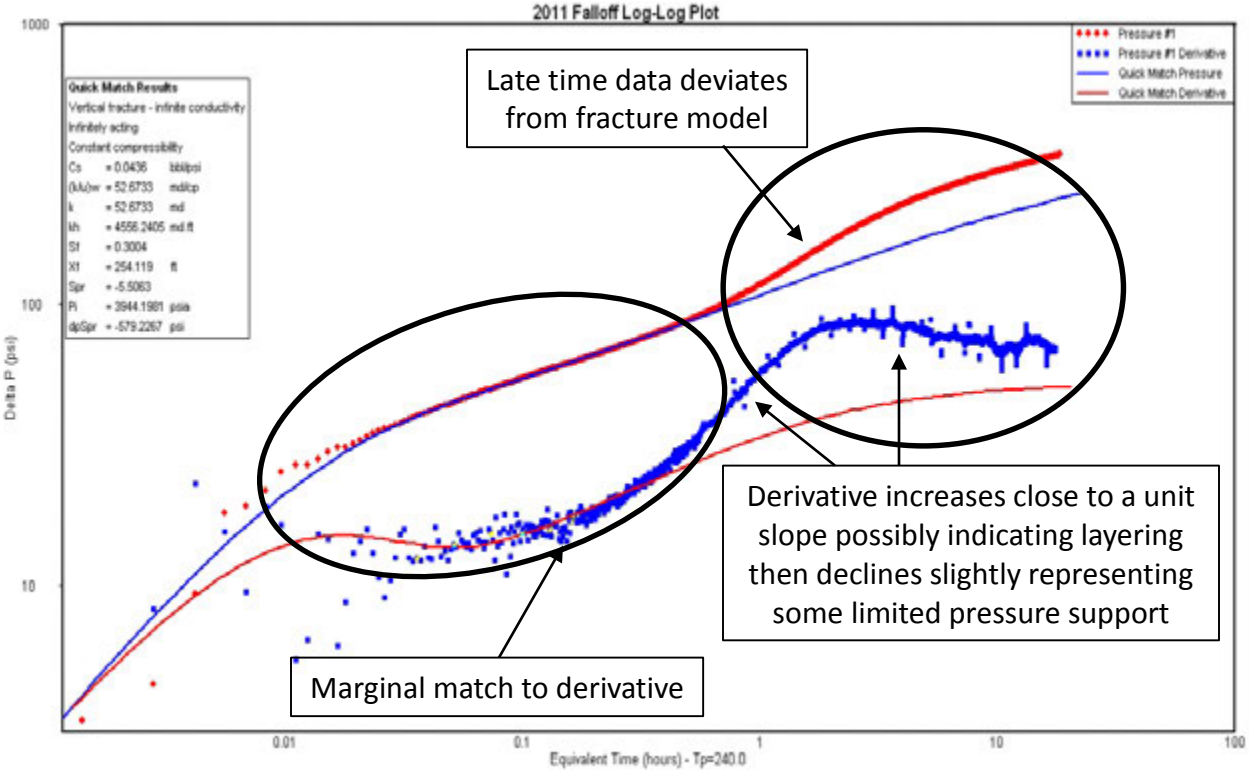


FIGURE E- 66: 2011 SPARKS TYPE CURVE MATCH



APPENDIX F: CENTRAL ARKANSAS AREA CASE STUDY

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All four case studies were considered in the development of the decision model. The state agencies' handling of these events was the basis for some of the approaches listed in the decision model described in APPENDIX B: . Consequently, the Injection-Induced Seismicity Working Group (WG) elected to apply the decision model framework to the case study events. Following the decision model framework, the wells in this case study fall under both the new and existing well categories. Increased earthquake frequency and magnitude following the start of disposal operations raised concern.

CENTRAL ARKANSAS CASE STUDY BACKGROUND

From 2009 through 2011, a series of earthquakes occurred near the towns of Guy and Greenbrier in Faulkner County, Arkansas. The news media initially attributed these quakes to hydraulic fracturing in the Fayetteville shale unconventional gas play illustrated in Figure F-1. Through deployment of additional seismographs, discussions with the various oil and gas operators, and

coordination between the Arkansas Oil and Gas Commission (AOGC), Arkansas Geologic Survey (AGS), and Center for Earthquake Research and Information (CERI) at the University of Memphis, a more descriptive geologic picture emerged, clarifying that the likely source of the activity was a previously unknown fault impacted by disposal activity.

To aid understanding of area site conditions, a summary of the geologic setting, existing oil and gas activity and seismic history is provided, followed by a focused site assessment and details of the disposal well operations.

Geologic Setting

The Greenbrier area is located in the Arkansas valley region of the eastern Arkoma basin. There are at least three phases of faulting as shown on the East Arkoma Basin structural cross-section in Figure F-2. (The location of the cross-section is shown in Figure F-1.) The most recent, normal listric[25] faults sole out on the Mississippian-Pennsylvanian unconformity. High-angle deeper normal faults extend into basement rock (Van Arsdale and Schweig, 1990). Not shown is the recently discovered Guy-Greenbrier fault[26] (Figure F-3), a near vertical, normal fault that cuts from the basement up through the upper Mississippian-Pennsylvanian unconformity at its northern extent (Horton, 2012; Horton and Ausbrooks, 2011; Personal communication, September 16, 2011).

The Paleozoic section contains alternating carbonates, shales and sandstones overlying crystalline basement rock. As illustrated in the stratigraphic column in Figure F-4, the Ozark confining unit separating the Boone and Hunton formations from the Ozark Aquifer[27] is thin or missing in the study area. The lower Ozark confining unit separating the Arbuckle from the Cambrian St. Francis Aquifer group and basement rock at the north end of the profile is also missing in this area. Thus, there may be little vertical confinement between disposal intervals and basement rock.

Oil and Gas Activity

The central portion of the Fayetteville shale gas play development started in 2004 and covers parts of Cleburne, Conway, Faulkner, Independence, Pope, Van Buren and White counties.

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[25] Listric faults can be defined as curved normal faults in which the fault surface is concave upwards; their dip decreases with depth. (http://www.geosci.usyd.edu.au/users/prey/ACSGT/EReports/eR.2003/GroupD/Report2/web%20pages/Listric_Faults.html)

[26] Note that the precise location and upper elevation depend on the particular velocity model used and vary between the two sources of information.

[27] The Ozark Aquifer is not a USDW in this area.

Fayetteville shale production wells typically use horizontal completions with laterals from 4,000 to 7000 feet in length at depths between 2,000 and 6,000 feet. Disposal prior to 2009 was in the Atoka and Hale formations above the Fayetteville shale. During the recent seismic activity, disposal was into the Boone through the Arbuckle formations. See Figure F-4 for the disposal zone formation sequence.

History of Seismicity

In 1811 and 1812, a series of magnitude 7 earthquakes rocked the New Madrid Seismic Zone, (USGS, 2011a). In 1982, Arkansas experienced the Enola swarm of earthquakes with the largest magnitude of 4.7 (USGS, 2011b), as illustrated on the timeline in Figure F-5. The more recent Greenbrier area earthquakes (2009–2011) were located 9 miles from the edge of the Enola swarm and approximately 100 miles from the edge of the New Madrid Seismic Zone, as shown in Figure F-1.

Focused Site Assessment

The earthquake activity near Greenbrier started in 2009 and continued prolifically into 2011. Five disposal wells injecting below the Fayetteville shale were active within the major area of seismic events. The focus study boundary, shown in Figure F-6, was based on earthquake activity and the regional seismometer network capabilities, along with the merging of an arbitrary 5 mile (8 km) radius around each of the five wells. The focused site assessment includes all pertinent information applied to the petroleum engineering review and case study findings.

Information Collected

Data for these five wells were collected from the AOGC website and from the state regulatory hearing documentation associated with the disposal well moratorium discussed later. Permitting documents provided details concerning completion depths, construction information, and permit conditions. Supplemental geosciences information was obtained from the deployment of additional seismometers. Operational monitoring reports provided several months of injection rates and wellhead pressures, with data being recorded as often as every hour in some wells.

Disposal Wells in Case Study Area

The five area disposal wells of interest are the Moore Estate 1-22, Edgmon 1, Trammel 7-13 1-8D, SRE 8-12 1-17, and Underwood 8-12 5-12. Data gathered from the permitting documents and operational reports for each well is summarized in Tables Table F-1 and Table F-2.

TABLE F-1: CENTRAL ARKANSAS FOCUS AREA WELLS PERMIT AND COMPLETION CONDITIONS

Disposal Wells (SWD)	Injection Permit Conditions					Completion Data (feet)				
	UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation	Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
Moore Estate 1-22	39487	Yes	3,000	6,000	Boone through Arbuckle: open-hole below 8,087'	7,760	10,600	10,600	5 ½" to 8,087'	2 7/8" to 8,077'
SRE 8-12 1-17	43266		3,330	20,000	Boone & Hunton	6,044	6,312	6,500	7" to 6,500'	4 ½" to 5,925'
Trammel 7-13 1-8D	41079	No	2,300	12,000	Boone	6,836	6,918	7,160	5 ½" to 7,126'	3 ½" to 6,800'
Underwood 8-12 5-12	42981	No	2,669	7,500	Boone, Chattanooga, Penters, Hunton & Viola; open-hole from 5619 to 6320'; Recompleted to Orr on 09/23/2010.	5,426	6,320	6,320	4 ½" to 5,521'	2 3/8" to 5,978'
Edgmon 1	36380	Yes	8,454	20,000	Arbuckle	7,280	10,970	12,163	4 ½" to 12,162'	2 7/8" to 7,710'

TABLE F-2: CENTRAL ARKANSAS FOCUS AREA WELLS OPERATING HISTORY

Disposal Wells (SWD)	Operations		
	Initial Disposal	Final Disposal	Plugged and Abandoned
Moore Estate 1-22	6/1/2009	7/15/2011	29-Sep-2011
SRE 8-12 1-17	7/8/2010	3/3/2011	30-Sep-2011
Trammel 7-13 1-8D	4/1/2009	6/20/2011	19-Oct-2011
Underwood 8-12 5-12	1/11/2010	6/27/2010	8-Mar-2011
Edgmon 1	8/18/2010	3/14/2011	

Additional Geosciences Information

Additional seismometers, designated Q and X, as illustrated in Figure F-7, were deployed in early September 2010 to investigate the Greenbrier area earthquakes through the combined efforts of AGS and University of Memphis CERI. Figures F-3 and F-7 show the fault, oriented N22°E, identified through interpretation of the monitor network results (Horton, 2012; AOGC, 2011. This fault was confirmed on 3-D seismic, courtesy of an area exploration company. Detailed information about the Greenbrier area earthquakes is available from the publications listed in Citations at the end of this appendix and in APPENDIX K.

The more recent Greenbrier area earthquakes recorded in the USGS Advanced National Seismic System (ANSS), ComCat (Comprehensive catalog), National Earthquake Information Center, U.S. Geological Survey (NEIC) and CERI catalogs, within the focus radius of the disposal wells of interest, are summarized in Table F-3 below and on a timeline illustrated in Figure F-8. A zoomed map area of the disposal well and earthquake activity is included on Figure F-6.

TABLE F-3: GREENBRIER AREA SEISMICITY THROUGH SEPTEMBER 30, 2013

Year	Starting Date	Number of Events	Magnitude			Ending Date
			Min.	Avg.	Max.	
2001	5/4/2001	4	2.7	3.2	4.3	5/5/2001
2002		0				
2003	12/14/2003	2	2.7	2.8	2.8	12/15/2003
2004		0				
2005	1/27/2005	1	2.7	2.7	2.7	1/27/2005
2006	4/9/2006	2	2.8	2.8	2.8	10/17/2006
2007		0				
2008		0				
2009	10/15/2009	7	2.4	2.7	3.0	10/31/2009
2010	2/18/2010	677	0.2	1.8	4.4	12/31/2010
2011	1/1/2011	732	1.0	2.2	4.7	12/22/2011
2012	1/14/2012	2	2.0	2.1	2.2	1/14/2012
2013	9/11/2013	4	1.6	1.9	2.1	9/28/2013

Operational Data

Data were divided into two areas: operational and pressure transient testing. All five wells had operational data for analysis. A step rate test was available for the Edgmon. Surface pressure

shut-in periods embedded[28] in the monitored pressure data for the Trammel, SRE and Edgmon wells were reviewed using pressure transient analysis techniques. Injection rates fluctuated significantly in all three wells prior to the shut-in periods. The shut-in pressures were recorded at the surface, so no useful pressures were available after a well went on a vacuum, making the pressure falloff responses of limited duration.

Operational data consisted of monthly and hourly wellhead pressures and injection volumes. The high data recording rate yielded fairly noisy data sets for operational analysis from intermittent use, but the added recording frequency provided sufficient data for a limited falloff test analysis during some of the shut-in periods. The Underwood well had very limited injection.

Surface pressures were converted to approximate bottomhole pressures (BHP) at the tubing seat depth of each well. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the surface pressure and pressure of the hydrostatic column of fluid and subtracting the calculated friction pressure loss. A fluid specific gravity of 1.025 was used based on permitting documentation for the SRE well.

Petroleum Engineering Review

Operational Analysis

Operational data were reviewed and analyzed for each of the five wells. No Hall plot was generated for the Underwood well. The Underwood had intermittent operating data, and suspect calculated friction losses due to combination of small diameter tubing and high injection rates. This resulted in inconsistent BHP calculations. The analysis plots are included in the following list of figures:

- Operational data overview plots: Figures F-9 through F-13
- Operating pressure gradient plots: Figures F-14 through F-18
- Tandem plot of Hall integral with derivative cumulative earthquake events: Figures F-19 through F-28

Table F-4 summarizes the assumed reservoir pressure value used in the Hall integral calculation for each Hall plot.

[28] The detailed operating data contained shut-in periods, effectively giving falloff test data.

TABLE F-4: HALL INTEGRAL INITIAL PRESSURE VALUES

Disposal Well (SWD)	Hall Plot Assumed Initial Pressure (psia)
Moore Estate 1-22	3,500
SRE 8-12 1-17	2,400
Trammel 7-13 1-8D	3,800
Edgmon 1	3,400
Underwood 1	n/a

A large number of small to moderate earthquake events were recorded during the period addressed by the Arkansas case study, making it possible to plot a detailed cumulative event trend. To determine if the earthquake cumulative event trend followed the Hall integral trend, tandem plots of cumulative earthquake events and Hall integral response versus cumulative water injection were prepared for the Moore Estate, SRE, Trammel, and Edgmon wells and are shown in Figures F-20, F-22, F-25, and F-27.

The operating pressure data analysis completed for each well is summarized below. The results of the tandem plots are also included.

The operating pressure data analysis completed for each well is summarized below:

- Operational data overview plots (Figures F-9 through F-13)
    - Moore Estate 1-22 (Figure F-9)
        - Tubing pressures did not fluctuate with rate changes
    - SRE 8-12 1-17 (Figure F-10)
        - Operated intermittently with significant rate fluctuations
        - Short falloff test during final well shut-in prior to well going on a vacuum
    - Trammel 7-13 1-8D (Figure F-11)
        - Rates dipped between January and June 2010 with limited pressure decline
        - Short falloff test during final well shut-in
    - Underwood 8-12 5-12 (Figure F-12)
        - Operated intermittently
    - Edgmon 1 (Figure F-13)
        - Operated intermittently with significant rate fluctuations
        - Falloff test recorded during final well shut-in
- Operating pressure gradient plots (Figures F-14 through F-18)
    - Highest operating gradients in the Moore Estate well (Figure F-14)
- Tandem plots of cumulative earthquakes and Hall integral with or without derivative (Figures F-19 through F-28)

- Moore Estate 1-22 (Figures F-19, F-20 and F-21)
    - Hall integral indicated some slope breaks
    - Derivative trend scattered
- SRE 8-12 1-17 (Figures F-22 and F-23)
    - SRE shut-in on March 4, 2011, with 2,471,012 bbls cumulative injection
    - Last 150 earthquake events occurred after well was shut in
    - Hall integral with derivative shows both positive and negative slope changes (Figure F-22)
    - Early slope breaks indicate possible enhanced injectivity (Figure F-23)
    - Gradual upward trend in Hall integral and derivative in last third of plot may suggest boundary, development of positive skin factor or response to offset disposal
- Trammel 7-13 1-8D (Figures F-24 and F-25)
    - Hall integral contains multiple positive and negative slope changes (Figure F-25)
    - Last half of Hall integral and derivative plot contains significant upward trends separated by a slight downward trend, but the overall upward trend may suggest boundary, development of positive skin factor or response to offset disposal (Figure F-24)
- Underwood 8-12 5-12 (No Hall integral or tandem plot generated)
- Edgmon 1 (Figure F-26, F-27 and F-28)
    - Hall derivative contains significant scatter from intermittent use, but trend remains below the Hall integral (Figure F-26)
    - Hall integral by itself shows multiple positive and negative slope changes, with some corresponding to earthquake events (Figure F-26 and F-27)

Pressure Transient Analysis

Edgmon 1 Step rate test (Figure F-29)

The WG reviewed the step rate test conducted in the Edgmon 1 well and found conflict between the reported data and field notes as summarized in Table F-5 and Table F-6. The data from the recorded data and field notes in Table F-6 were used for preparation of the linear plot. A drastically reduced pressure response occurred during rate step 6. The small diameter tubing size in the well coupled with high injection rate values resulted in the calculated BHPs dropping below the actual measured surface pressures due to severe calculated friction loss. No slope breaks were observed in the surface pressure data. The test was not considered suitable for quantitative analysis.

TABLE F-5: EDGMON 1 STEP RATE TEST DATA FROM APRIL 10, 2010, TEST REPORT*

Step	Injection Rate (BPM)	Injection Rate (BPD)	Surface Injection Pressure (psig)	Frictional Pressure (psig)	Estimated Hydrostatic Pressure (psig)	Estimated BHP Pressure (psig)
1	5.9	8,500	760	710	3,465	3,515
2	7.0	10,100	1,204	1,134	3,465	3,535
3	8.4	12,100	1,704	1,584	3,465	3,585
4	9.9	14,200	2,380	2,125	3,465	3,695
5	11.2	16,100	3,015	2,715	3,465	3,765
6	14.4	20,800	4,960	4,360	3,465	4,065
7	17.4	25,000	6,882	6,097	3,465	4,250

*** EDGMON DATA SUMMARY TABLE IN REPORT LISTED INCONSISTENT TIME INCREMENTS AND INJECTION RATES COMPARED TO THE DATA FROM THE RECORDING INSTRUMENTS AND FIELD NOTES INCLUDED IN THE REPORT. TIME INCREMENTS = 15 MINUTES; WATER WEIGHT = 8.55 PPG; WATER SPECIFIC GRAVITY = 1.025; DEPTH TO TOP PERFORATION = 7,806 FEET.**

TABLE F-6: EDGMON 1 2010 STEP RATE TEST DATA FROM RECORDED DATA AND FIELD NOTES*

Step	Rate from data (BPM)	Rate (gpm)	Surface Pressure (psig)	Bottomhole Pressure (psig)	Friction Pressure (psi)	Bottomhole Pressure Corrected for Friction (psig)	Time Increments (min)
1	5.8	243.6	760	4,182	1,200	2,982	60
2	6.9	289.8	1,204	4,626	1,655	2,971	60
3	8.3	348.6	1,675	5,097	2,329	2,768	60
4	9.9	415.8	2,380	5,802	2,337	2,575	60
5	11.1	466.2	3,015	6,437	3,988	2,449	60
6	11.2	470.4	1,090	4,512	4,055	457	60
7	14.8	621.6	4,997	8,419	6,791	1,628	180

*** EDGMON SUMMARY TABLE COMPILED FROM RECORDED DATA AND FIELD NOTES. PRESSURE DROPPED DURING RATE STEP 6; REPORT PROVIDED NO EXPLANATION FOR PRESSURE DECREASE.**

Surface pressure falloff test data were also reviewed for the Trammel, SRE and Edgmon wells using PanSystem® well test analysis software. The final falloff periods were analyzed and the reservoir characteristics are illustrated in Figures F-30 through F-32 for the three disposal wells located closest to the Guy-Greenbrier fault. The rate variations for each well were accounted for by the use of equivalent time on the log-log plot. The pressure transient analysis of the step rate test for the Edgmon and the final falloff tests for the Trammel, SRE and Edgmon are summarized below:

- Edgmon 1 step rate test (Figure F-29)
    - Linear plot of surface pressure test data converted to bottomhole
        - Anomalous behavior observed during step 6
            - At a constant injection rate of 11.2 BPM the surface injection pressure fluctuated greatly
                - Started at approximately 2,860 psi for 5 min
                - Dropped abruptly to approximately 960 psi
                - Climbed gradually to approximately 1,090 psi
        - Calculated BHPs declined with increasing injection rates
            - Friction factor of 140 resulted in a negative bottomhole pressure for the final rate step, so friction factor of 150 used for step rate analysis only
- SRE 8-12 1-17 Final falloff test (Figure F-30)
    - Overview plot of shut-in periods and final falloff (Figure F-10)
    - Log-log plot indicated a fracture or highly stimulated completion signature
        - Matched using an infinite conductivity fracture model (Figure F-30)
        - Indicated a long fracture half-length (> 500 feet) for this well's completion
        - Late test time derivative response declined
- Trammel 7-13 1-8D Final falloff test (Figure F-31)
    - Overview plot of shut-in periods and final falloff (Figure F-11)
    - Log-log plot indicated a fracture or highly stimulated completion (Figure F-31)
        - Completely dominated by linear flow
        - Could not be type curve matched
- Edgmon 1 Final falloff test (Figure F-32)
    - Overview plot of shut-in periods and final falloff (Figure F-13)
    - Log-log plot (Figure F-32)
        - Response was dominated by wellbore storage and was unanalyzable

Summary of Engineering Analysis

A total of four pressure transient tests were reviewed for the Arkansas case study area. The Edgmon disposal well had both a planned step rate test and an inadvertent falloff test embedded in surface pressure data. Two other injection wells, the SRE and Trammel, also had inadvertent falloff tests of limited duration embedded in their surface pressure data sets.

The Edgmon step rate test showed a decline in surface pressure during one of the later steps at a higher injection rate and was not suitable for analysis. Despite having surface pressure, the Edgmon falloff test was dominated by wellbore storage; consequently, it was also unanalyzable. The SRE and Trammel falloffs were dominated by linear flow, as shown in Figures F-30 and F-31,

indicating the presence of significantly long fracture connected to each disposal well. The presence of a fracture at each well would focus the dispersion of the well's injection pressure directionally along the fractures rather than radially.

Operational data were reviewed for the five injection wells: Moore Estate, SRE, Trammel, Edgmon, and Underwood. The Underwood well operated intermittently so its data were unsuitable for analysis. Due to the more frequent monitoring of the operational behavior of the four remaining wells, both the operational gradient and the Hall derivative tended to be much more scattered. The operating gradient plot for the Moore Estate well showed the highest consistent operating gradient with many values between 0.8 to 0.9 psi/foot while the Edgmon well's operating gradient showed three time periods with upward spikes to gradient values as high as 0.8 psi/foot. The Trammel well's operating gradient generally fell between 0.65 and 0.75 psi/foot. The SRE well's operating gradient was noticeably lower than the other three disposal wells, generally staying between 0.55 to 0.65 psi/foot.

The Moore Estate, SRE, Trammel, and Edgemon tandem plots all showed some correspondence between clusters of seismic events and decreases in ease of injection in the form of upward slope breaks in the Hall integral trend. All of the tandem plots shows periods of both declining and increasing Hall integral trends. The Trammel tandem plot showed the strongest correspondence between declining ease of injection in both Hall integral and derivative trends in the form of upward shifts and corresponding seismic event clusters.

Actions Taken by UIC Regulatory Agency in Central Arkansas Area

The initial response was deployment of additional seismometers to better record the actual event epicenters (surface locations) and focus locations (depth). This was done through the combined efforts of AGS and CERI, with some of the monitor stations directly linked into the U.S. Geological Survey National Earthquake Information Center.

Following initial identification of the Guy-Greenbrier fault, the AOGC established a moratorium in December 2010 on the drilling of any new Class II disposal wells in an area surrounding and in the immediate vicinity of the seismic activity, and it also required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide hourly injection rates and pressures on a biweekly basis for a period of 6 months, through July 2011. During the moratorium period AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship. (The injection-induced seismicity project considered the five deeper wells closest to the Guy-Greenbrier fault selecting the three wells closest to the fault for further analysis.)

Using Wells and Coppersmith (1994) equations, from the estimated fault rupture length and area, the potential maximum (moment) magnitude the fault in Figure F-5 could produce was estimated to be between 5.6 and 6.0. (Horton, 2011)

In February 2011, following a series of larger magnitude earthquakes, (4.7, with damage reported), the operators of the three disposal wells nearest the seismic activity (SRE, Trammel and Edgmon) voluntarily agreed to shut in the subject disposal wells prior to the issuance of an AOGC cessation order. The subsequent March 4, 2011, cessation order required the subject wells to cease disposal operations. In July 2011, following the conclusion of the moratorium study, the AOGC established a revised permanent moratorium area in which no further Class II disposal wells could be drilled, and four of the original seven disposals wells included in the original moratorium area were required to be plugged. The revised moratorium area was based on the trend of the fault identified as the cause of the seismic activity. The order of the AOGC issued in July 2011 became a final administrative regulation on February 17, 2012. (Note: the operator of the Edgmon disposal well is in bankruptcy and the well will probably be plugged by the AOGC under the AOGC's Abandoned and Orphaned Well Plugging Program).

Resulting Changes in Regulations and Practices

The AOGC finalized amendments to its Class II disposal well rules effective in February 2012. Since July of 2011, the AOGC, AGS and CERI have continued to monitor disposal well operations and seismic activity. Additional seismic monitoring equipment has been purchased to provide an "early warning" system for emerging seismic activity, thereby allowing more time to develop appropriate responses.

Central Arkansas Area Multidisciplinary Integration of Findings

Evaluation of the focus area geology, as discussed above and in the cited publications, shows several possible pathways by which pressure buildup could reach the activated Guy-Greenbrier fault through various formations open in several of the disposal wells. Engineering analysis for this case study was based on increased frequency of monitoring data using disposal well surface pressures and rates, resulting in a significant amount of scatter in the data sets. The falloff tests embedded in the monitoring data indicated significantly long fractures connected to two of the disposal wells.

The operational data analysis, while impacted by data scatter, displayed cycles of upward and downward shifts in both the Hall integral and derivative trends on the various tandem plots for the four disposal wells with adequate monitoring history. As in other case studies, the upward shifts had at least some correspondence to area seismic events. The cyclic tandem plot patterns, when considered in conjunction with the area geology, embedded pressure transient tests, and

the operating gradient plots, likely reflect a combination of reservoir rock heterogeneities, fracturing occurrence in the wells in the form of enhanced injectivity, and interaction with reservoir boundaries such as a fault.

CENTRAL ARKANSAS AREA LESSONS LEARNED

- Initiating dialogue with operators can result in early voluntary action, including well shut-in or acquisition of additional site data.
    - Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut-in of some suspect disposal wells.
    - An operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep-seated fault.
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.
    - Hall integral and derivative plot may indicate a no-flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance.
    - Hall integral and derivative plot may illustrate enhanced injectivity.
- Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation, or an increased permeability zone at distance.
- Acquisition of additional data may provide an improved analysis.
    - Increased recording of operational parameters can improve the quality of the operational data analysis.
        - Increased frequency of monitoring for permit parameters improved the operational analysis.
- Engaging external geophysical expertise may allow more accurate determination of the location (x,y,z) of the active fault and stress regime, through reinterpretation or increased seismic monitoring.
    - Especially important as earthquake event magnitudes increased over time.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
    - Additional stations resulted in reliable identification of active fault locations.
- Engage a multidisciplinary combined approach to minimize and manage induced seismicity at a given location.
    - Working with state geological survey or university researchers provided expert consultation, resulted in installation of additional seismometers, and yielded a clearer understanding of the deep seated active faulting.
- Director discretionary authority was used to solve individual site-specific concerns:

- The Director acquired additional site information, requested action from operators, and prohibited disposal operations. Specific examples include:
  - Increased monitoring and reporting requirements for disposal well operators to provide additional operational data for reservoir analysis.
  - Required one well to install a seismic monitoring array prior to disposal as an initial permit condition.
  - Required plugging or temporary shut-in of suspect disposal wells linked to injection-induced seismicity while investigating or interpreting additional data.
  - Defined a moratorium area prohibiting Class II disposal wells in defined high risk area of seismic activity.

CITATIONS

ANSS: <http://quake.geo.berkeley.edu/cnss/ >

AOGC: < http://www.aogc2.state.ar.us/July_2011_Hearing_Orders.htm>;

<http://www.aogc2.state.ar.us/July_2011_Hearing_Apps_Archive.htm>

<http://www.aogc.state.ar.us/OnlineData/Forms/Rules and Regulations.pdf ;

<http://www.aogc2.state.ar.us:8080/DWClient/View1.aspx?DWSubSession=5756&v=1589 >

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ComCat: <http://earthquake.usgs.gov/earthquakes/search/>.

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Wells, D. L., and K. J. Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

APPENDIX F FIGURES

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Figure F- 32: Edgmon Log-log Plot of Pressure Falloff During Final Shut-in of WEll *36*

FIGURE F- 1: CENTRAL ARKANSAS CASE STUDY REGIONAL AREA

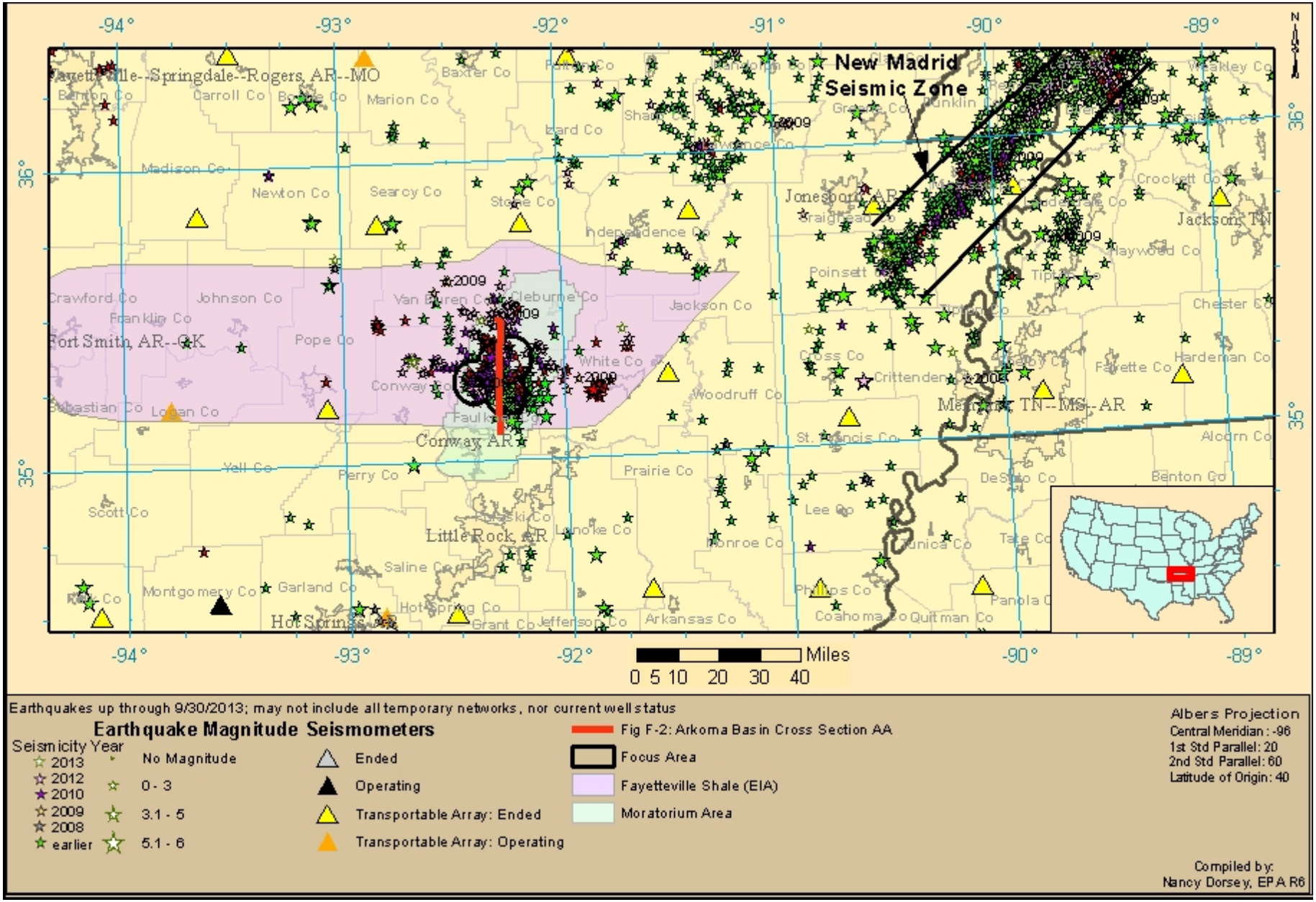
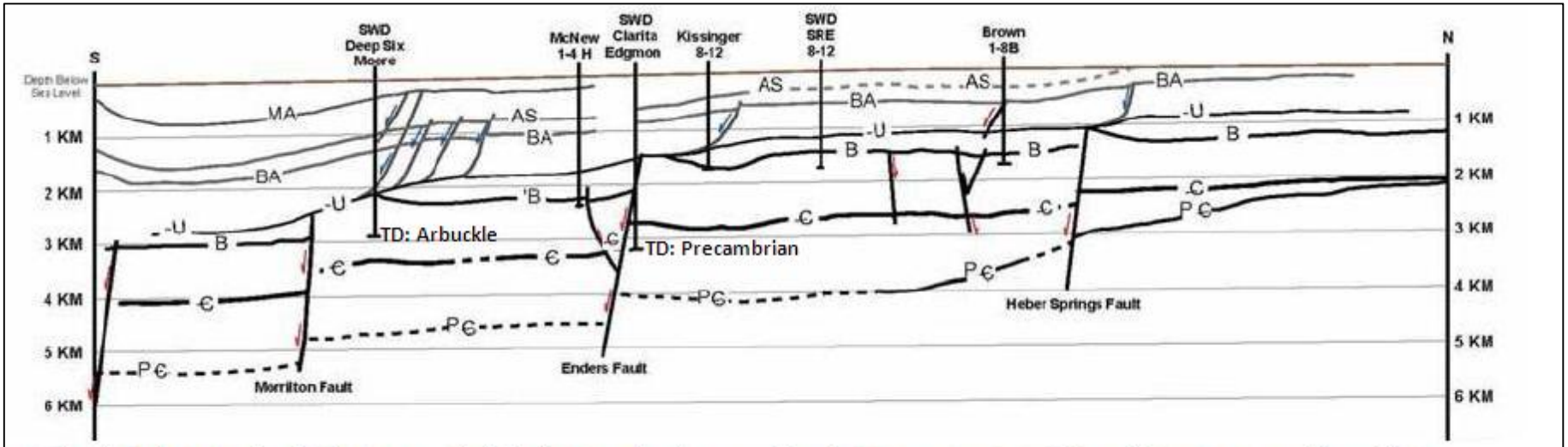
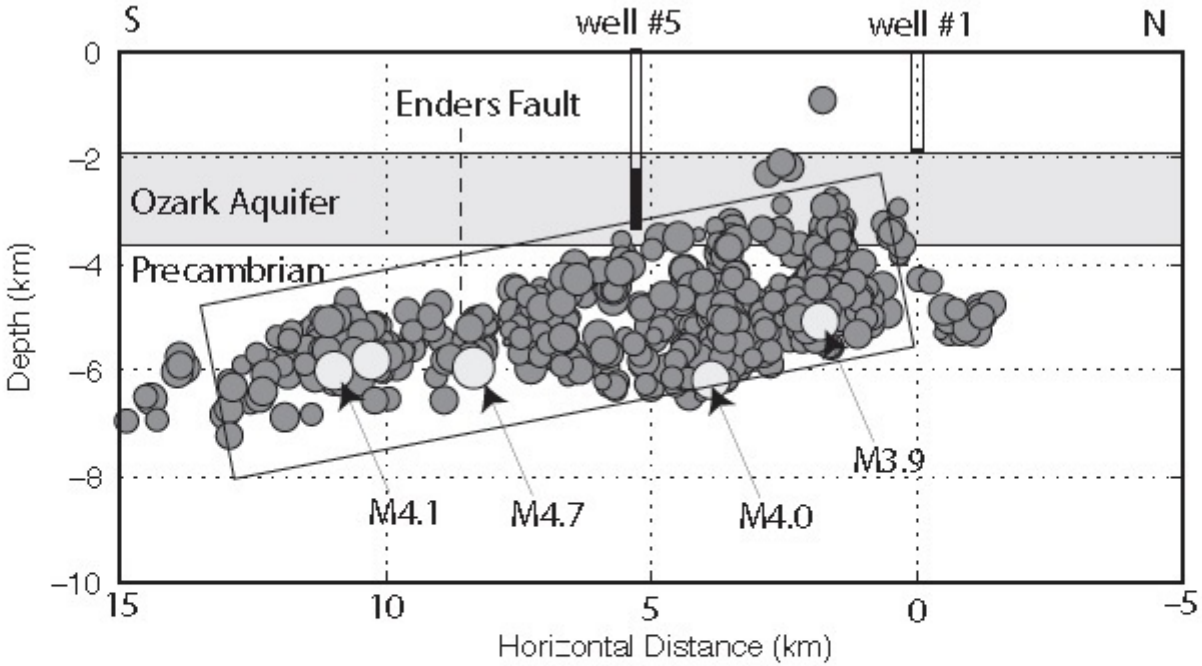


FIGURE F- 2: EAST ARKOMA BASIN STRUCTURAL CROSS-SECTION (WITH PERMISSION)



MA: basal Atoka SS BA: basal Atoka SS unc: Mississippian-Pennsylvanian unconformity B: Boone Fm C: Cambrian reflector Pc: Precambrian reflector
From Ausbrooks Exhibit 23 based on Vanarsdale and Schweig, Subsurface Structure of the Eastern Arkoma Basin, AAPG Bulletin, V. 74, N. 7, p. 1030-1037, 1990.

FIGURE F- 3: CROSS-SECTION OF ACTIVE FAULT PLANE (FIGURE 3 OF HORTON, 2012)

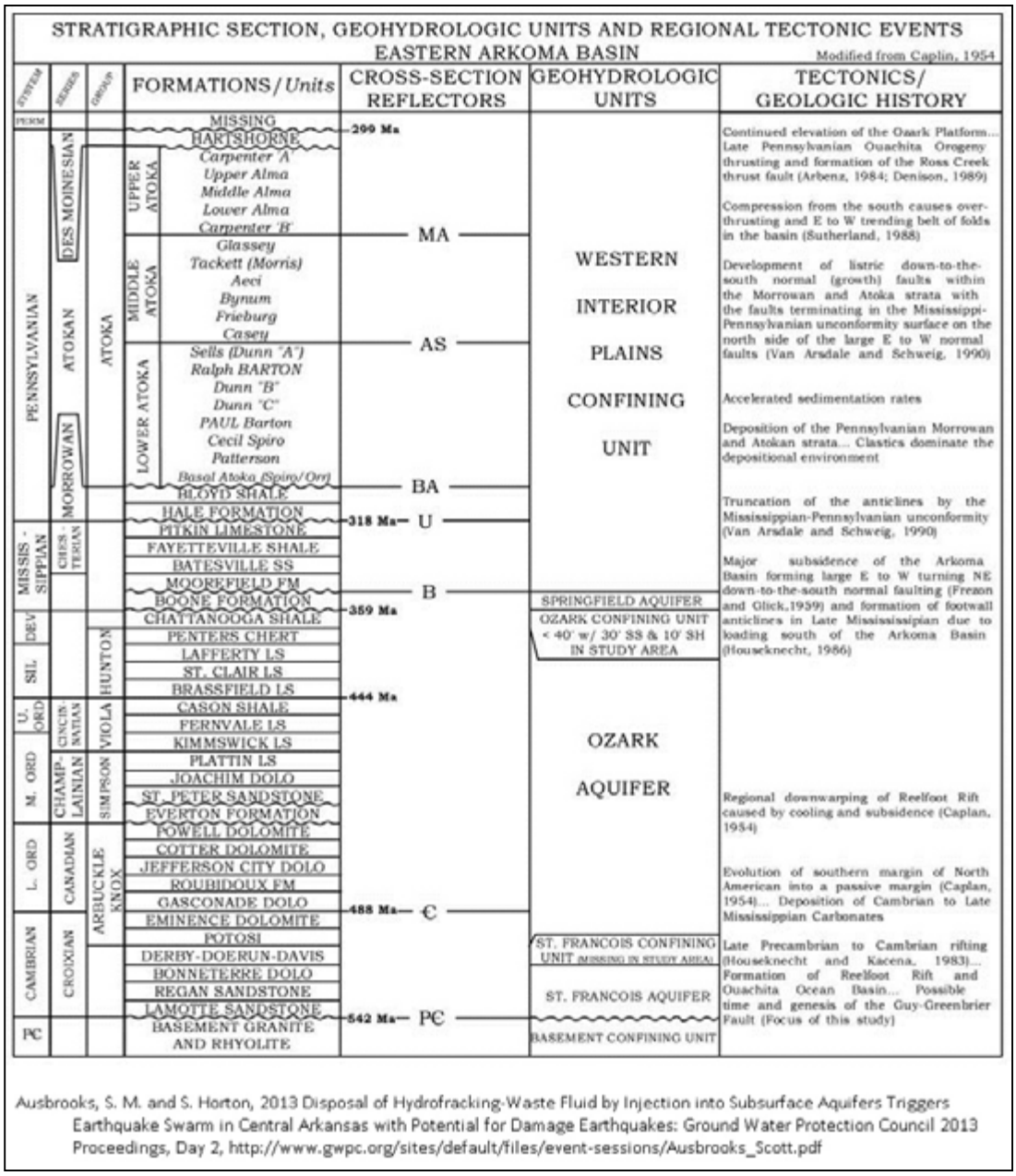


▲ **Figure 3.** Cross-section showing earthquake hypocenters looking N60W. Rectangle is 13 × 3.2 km and dips 11°. Shaded rectangle indicates the approximate vertical extent of the Ozark aquifer with the bottom boundary depth determined in well #5 and the top boundary depth determined in well #1. Solid black portion of each well indicates the interval where fluid is injected. The dashed line indicating the Enders fault is approximate. The larger earthquakes (light gray circles) rupture the deeper portions of the fault.

Horton, S. P., 2012, Disposal of Hydrofracking-waste fluid by injection into subsurface aquifers triggers earthquake swarm in Central Arkansas with potential for damaging earthquakes: Seismological Research Letters, v. 83, p. 250-260, doi: 10.1785/gssrl.83.2.250.

Wells: 1 = SRE 8-12 1-17; 5 = Edgmon 1

FIGURE F- 4: STRATIGRAPHIC AND HYDROLOGIC COLUMN OF THE ARKOMA BASIN (AUSBROOKS AND HORTON, 2013)



Ausbrooks, S. M. and S. Horton, 2013 Disposal of Hydrofracking-Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damage Earthquakes: Ground Water Protection Council 2013 Proceedings, Day 2, http://www.gwpc.org/sites/default/files/event-sessions/Ausbrooks_Scott.pdf

FIGURE F- 5: CENTRAL ARKANSAS HISTORIC AREA SEISMICITY IN FOCUS AREA THROUGH 9/30/2013

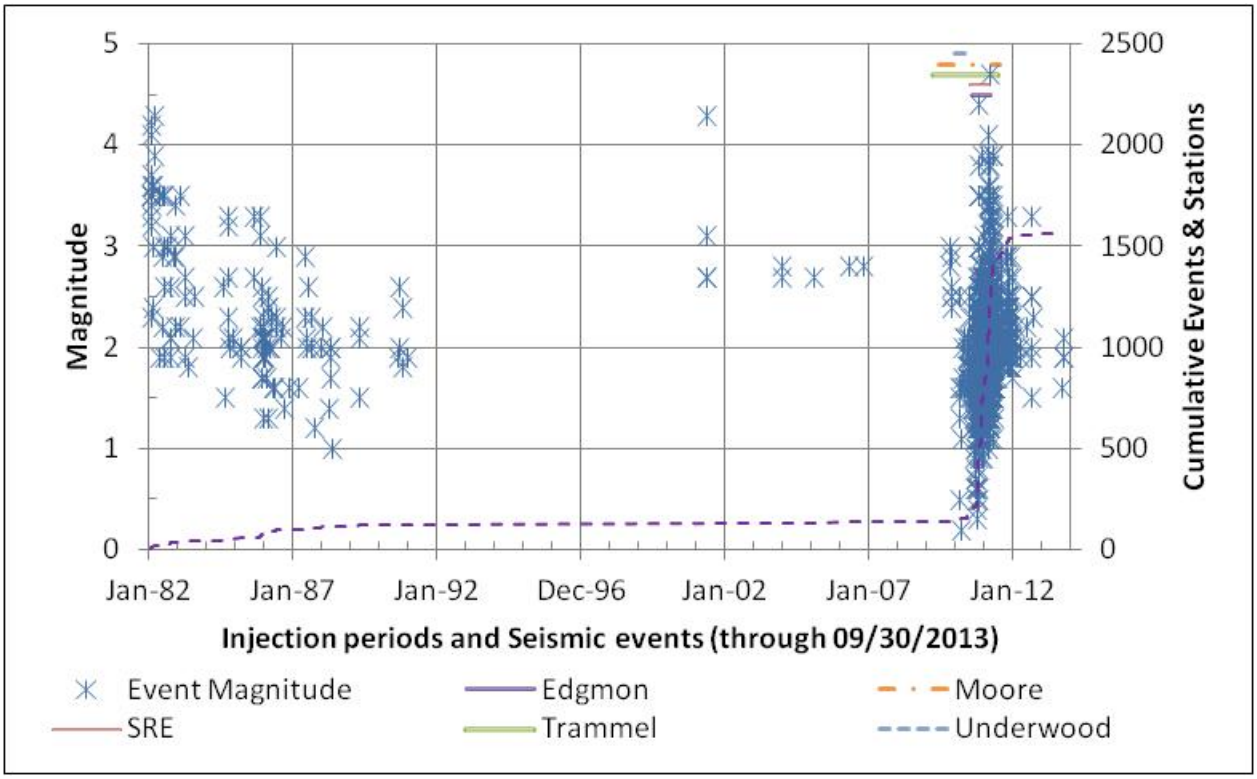


FIGURE F- 6: COMPOSITE FOCUS AREA SEISMICITY MAP

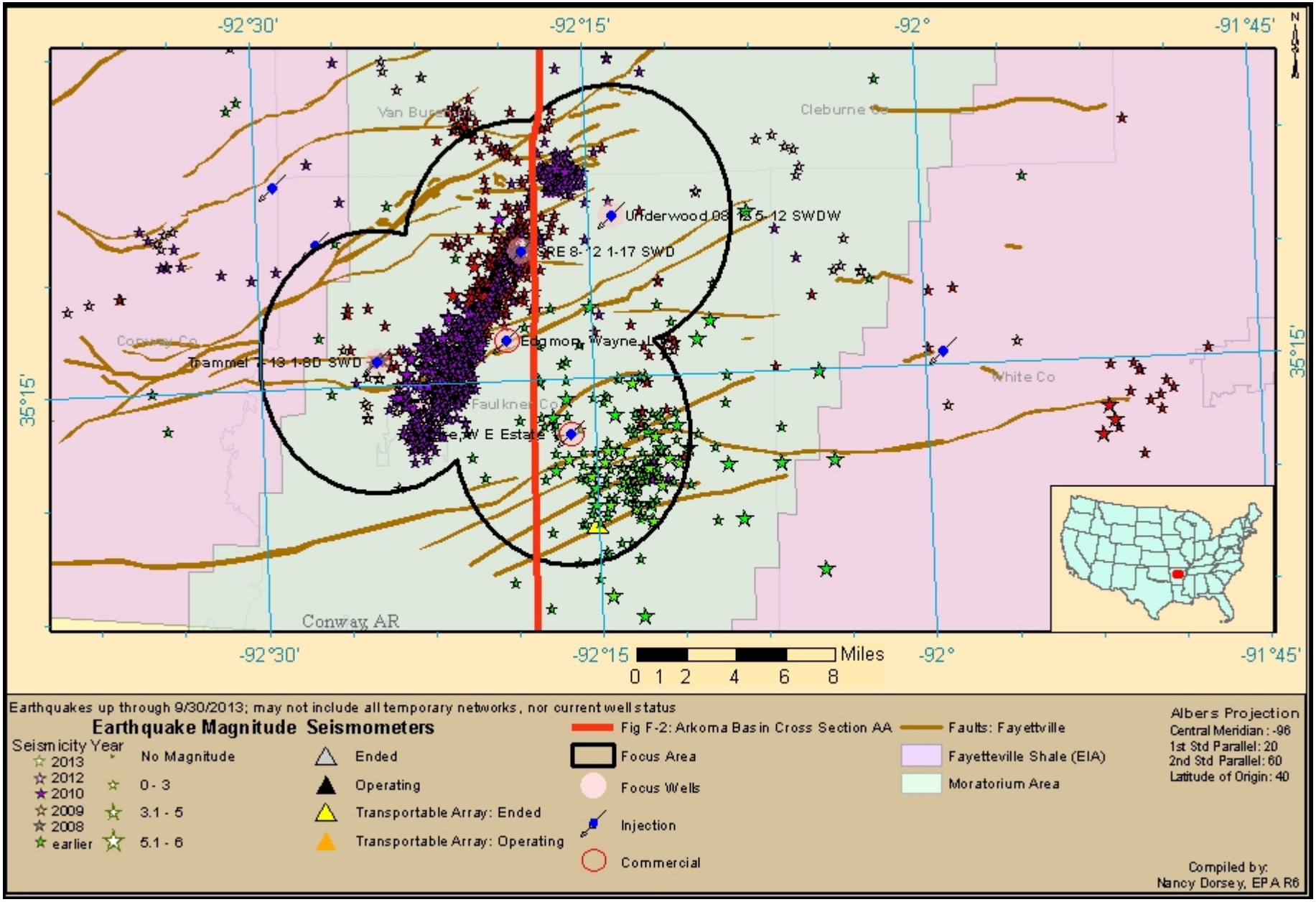
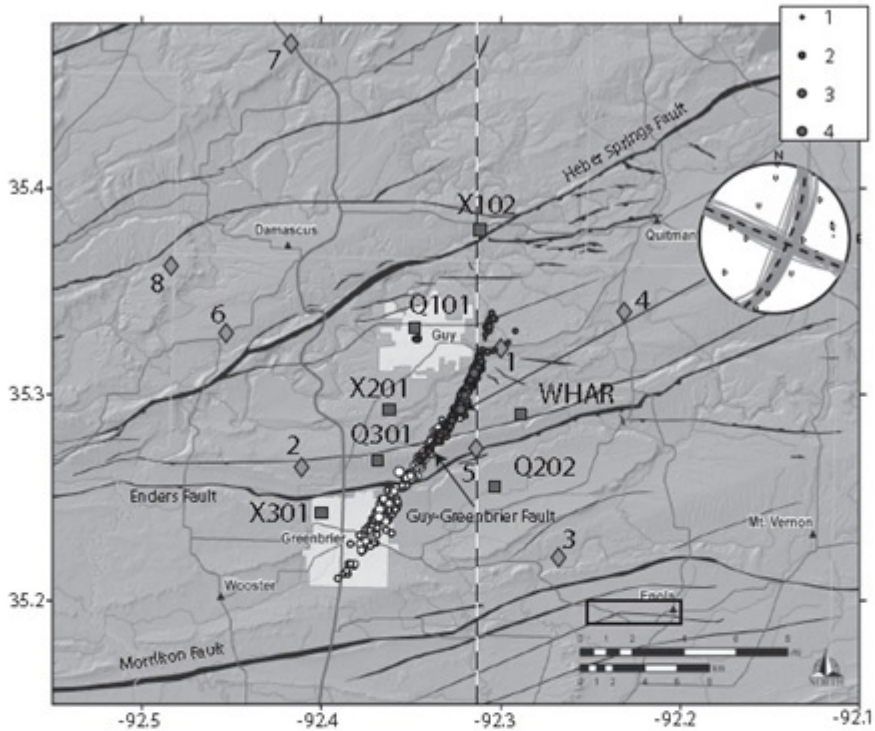


FIGURE F- 7: SEISMOMETER DEPLOYMENT AND ACTIVE FAULT TRACE (HORTON, 2012)



▲ **Figure 2.** Seismic stations (black squares), UIC wells (gray diamonds, Table 1), earthquakes (dark gray filled circles) between 1 October 2010 and 15 February 2011, and earthquakes (white filled circles) between 02/16/11 and 03/08/11. Named faults penetrate to the Precambrian basement (faults from AGS and AOGC). Earthquakes were located using HypoEllipse (Lahr 1999) and the velocity model of Chiu *et al.* (1994), then relocated using hypoDD (Waldhauser 2001) with the same velocity model. Inset: First-motion focal mechanism for **M** 4.0 earthquake on 11 October 2010 is consistent with right-lateral strike-slip on a NE oriented fault. North/south dashed line coincides with the geologic cross-section in Figure 4.

Horton, S. P., 2012, Disposal of Hydrofracking-waste fluid by injection into subsurface aquifers triggers earthquake swarm in Central Arkansas with potential for damaging earthquakes: Seismological Research Letters, v. 83, p. 250-260, doi: 10.1785/gssrl.83.2.250.

Wells 1 = SRE 8-12 1-17; 2 = Trammel 7-13 1-8D; 3=Moore 1-22; 4=Underwood 8-12 5-12; 5 = Edgmon 1

FIGURE F- 8: CENTRAL ARKANSAS COMPOSITE FOCUS AREA SEISMICITY

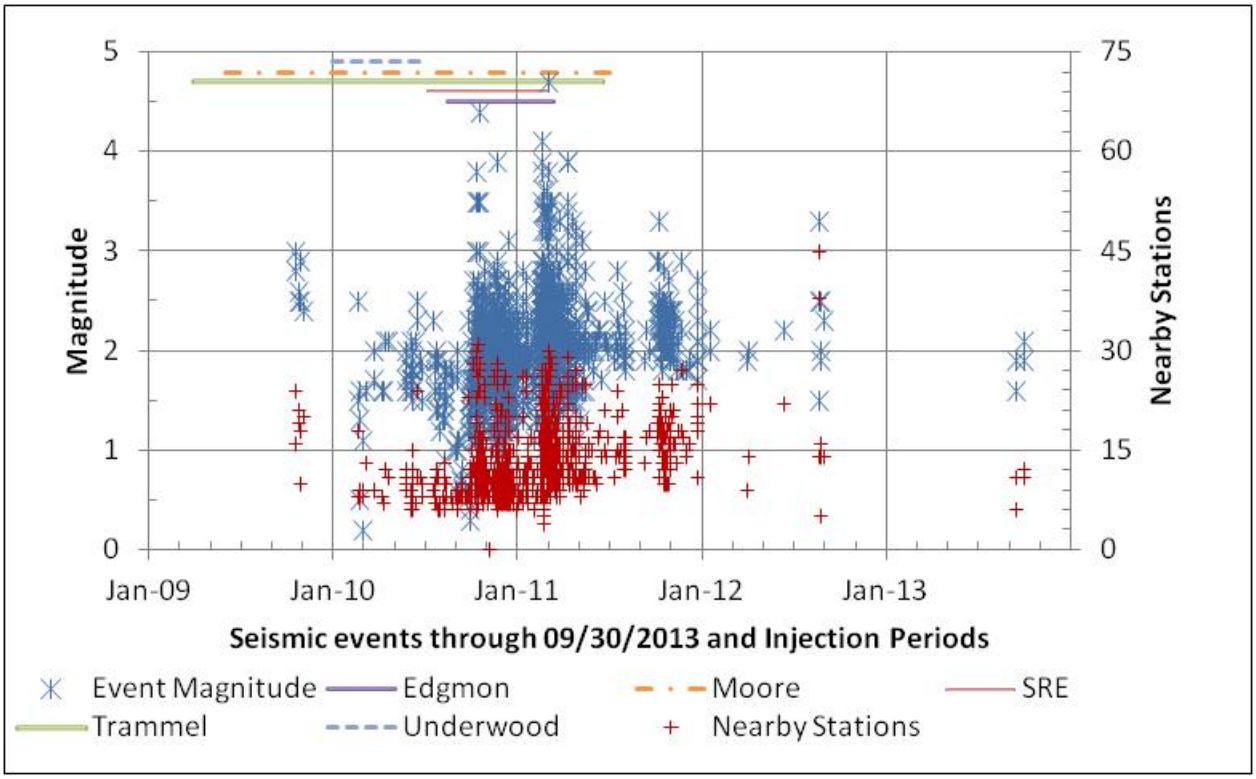


FIGURE F- 9: MOORE ESTATE OPERATIONAL DATA PLOT

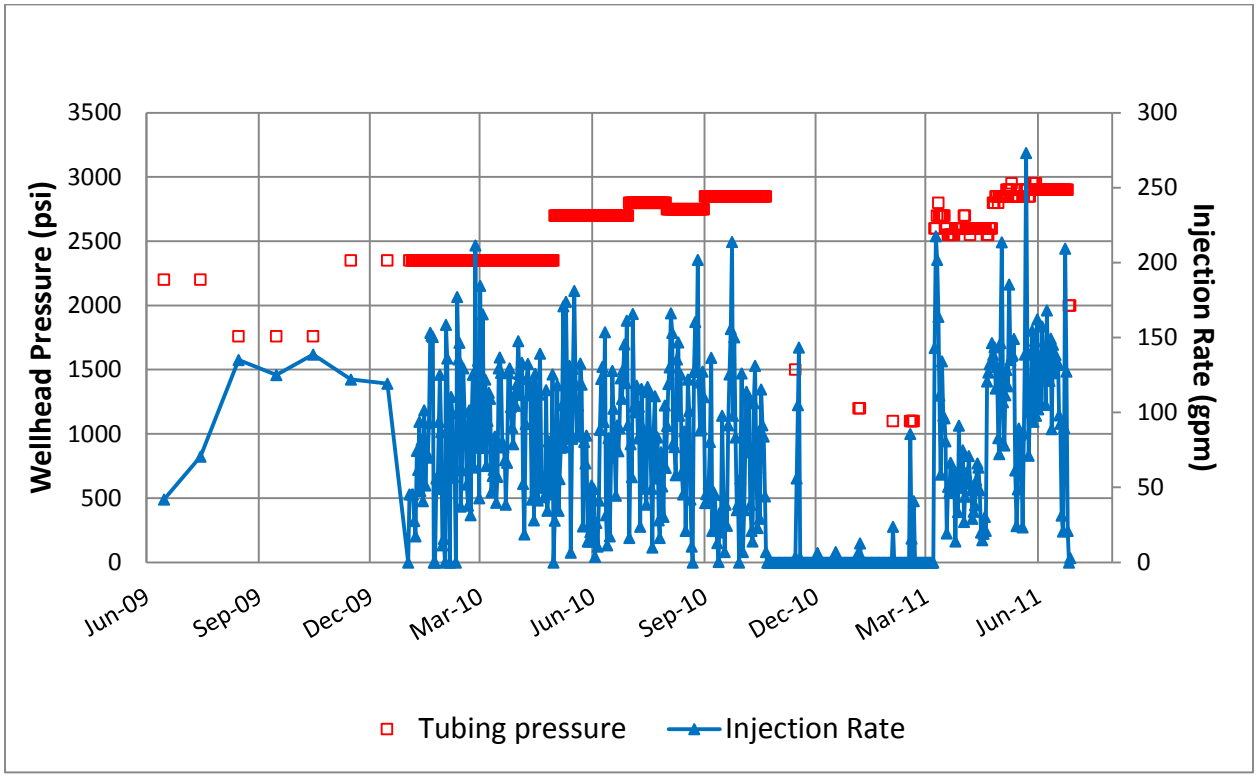


FIGURE F- 10: SRE OPERATING DATA PLOT

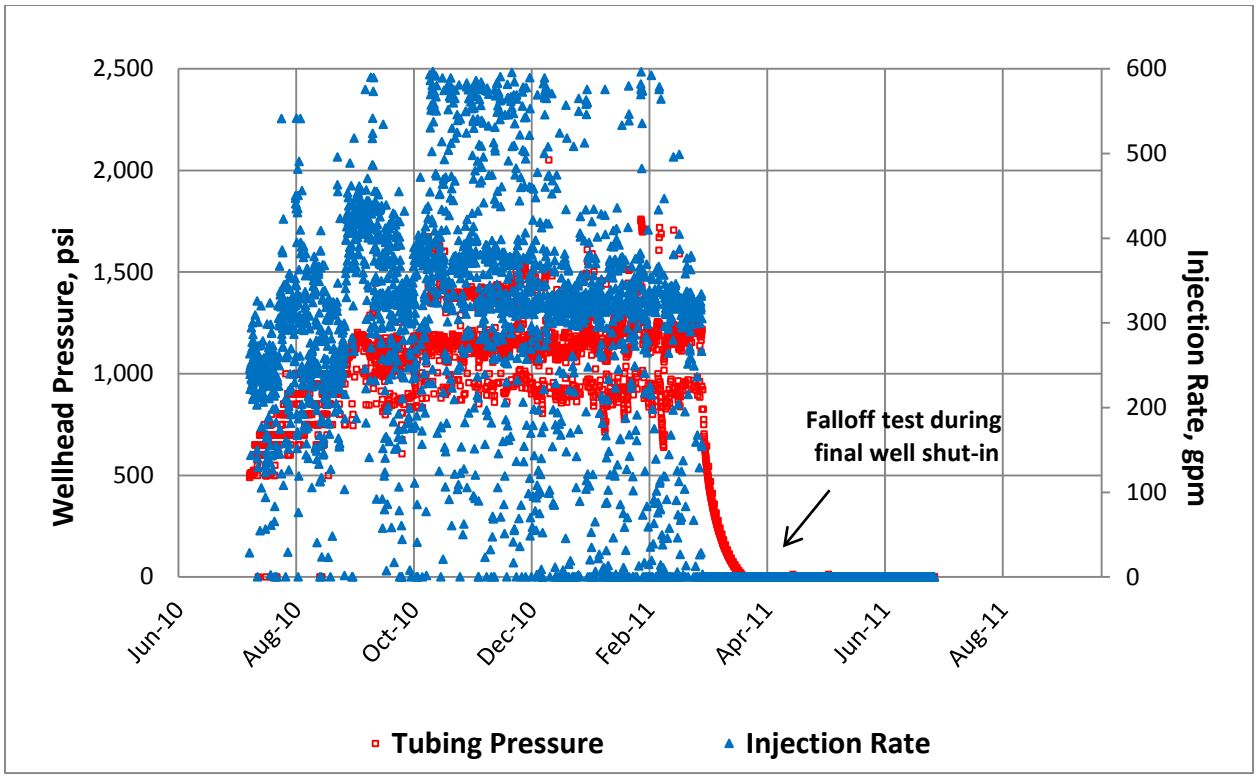


FIGURE F- 11: TRAMMEL OPERATING DATA PLOT

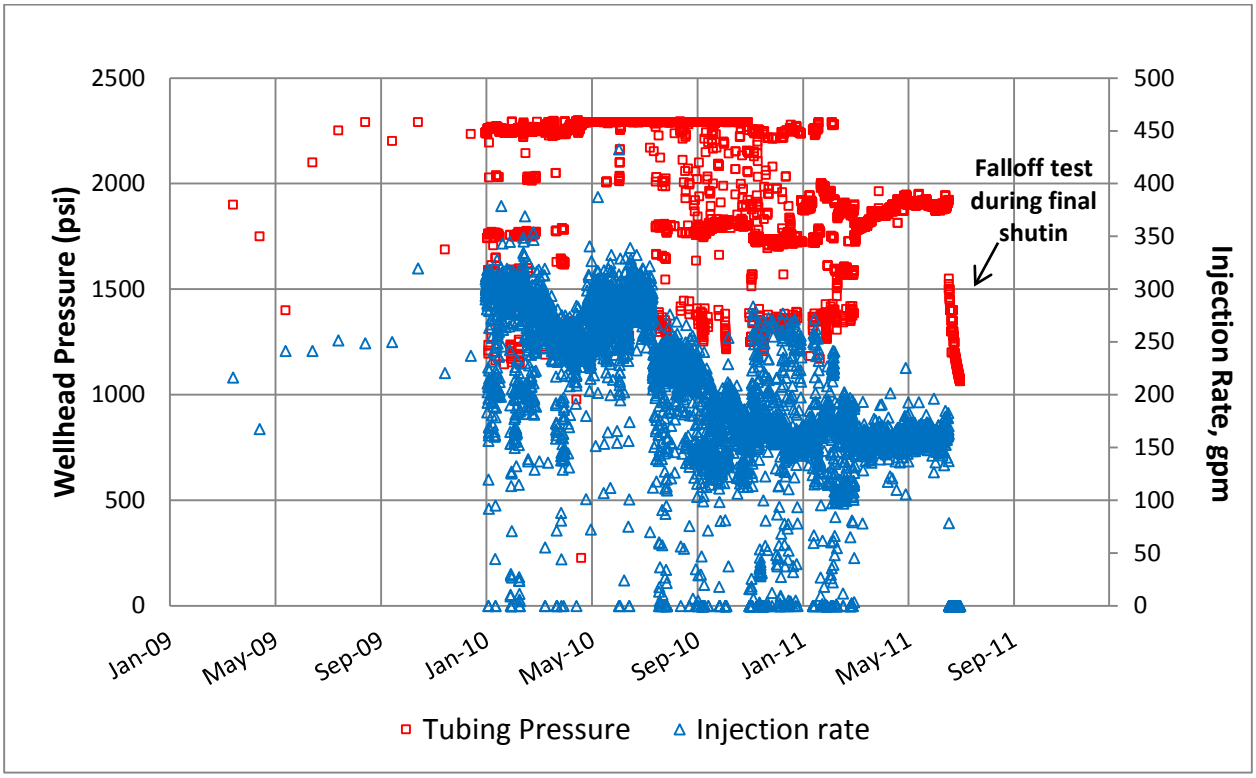


FIGURE F- 12: UNDERWOOD OPERATING DATA PLOT

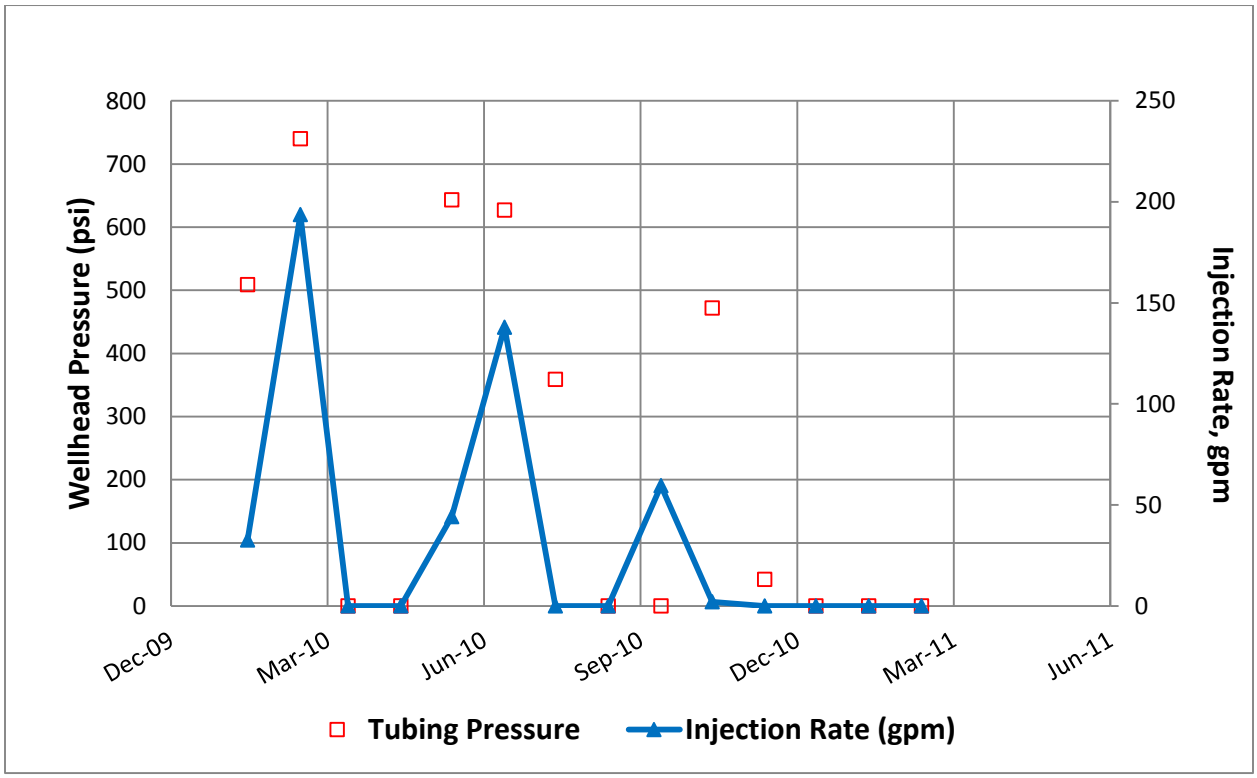


FIGURE F- 13: EDGMON OPERATING DATA PLOT

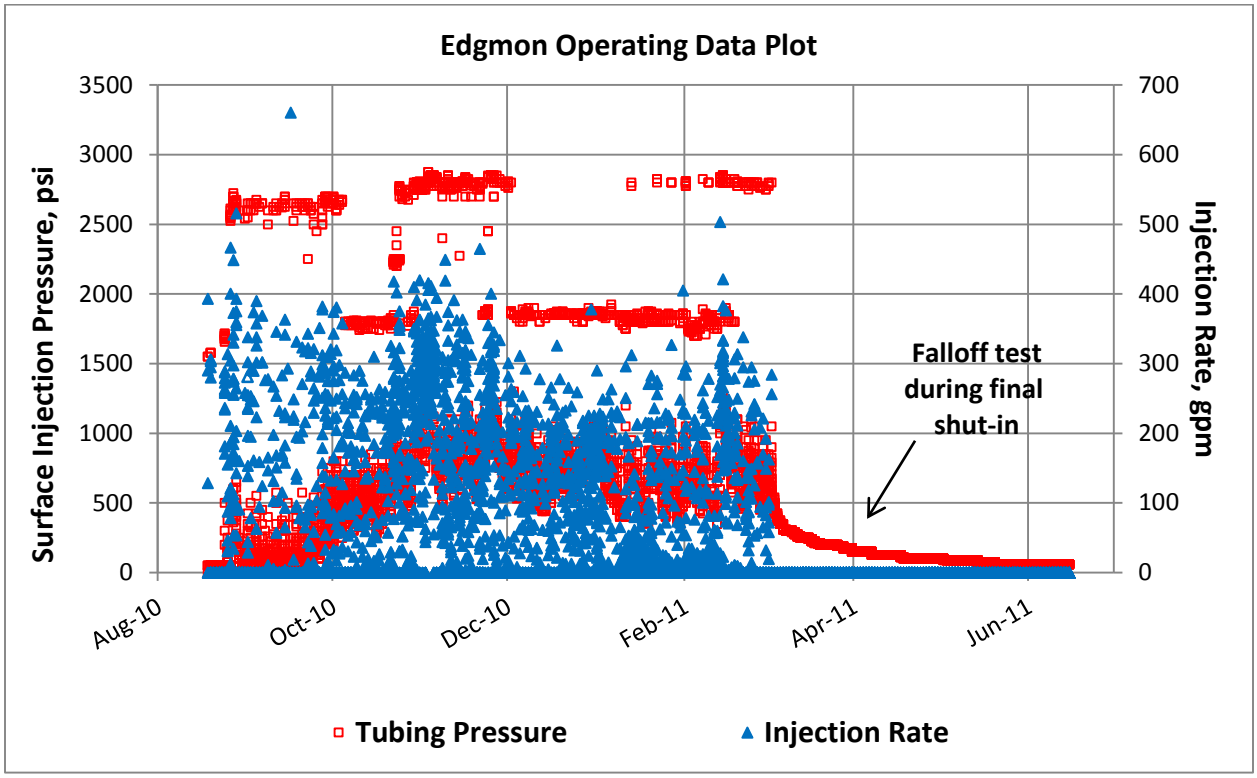


FIGURE F- 14: MOORE ESTATE OPERATING PRESSURE GRADIENT PLOT

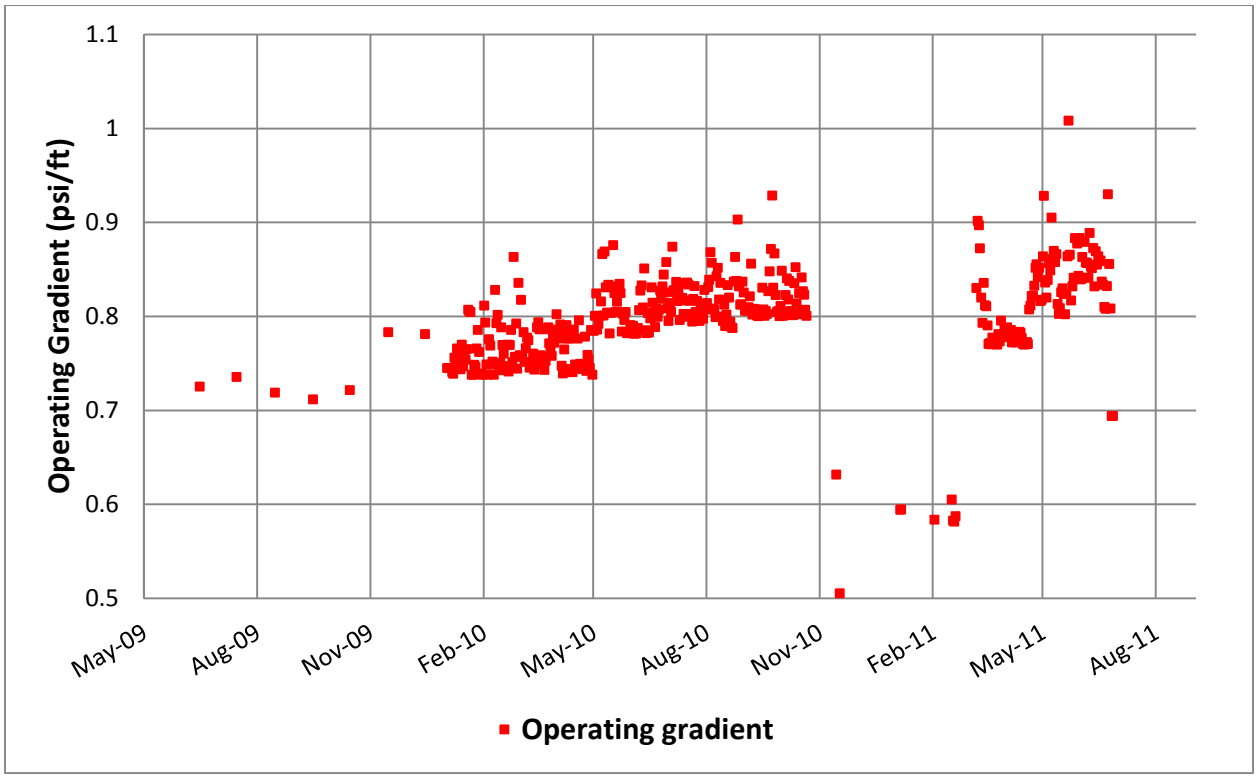


FIGURE F- 15: SRE OPERATING PRESSURE GRADIENT PLOT

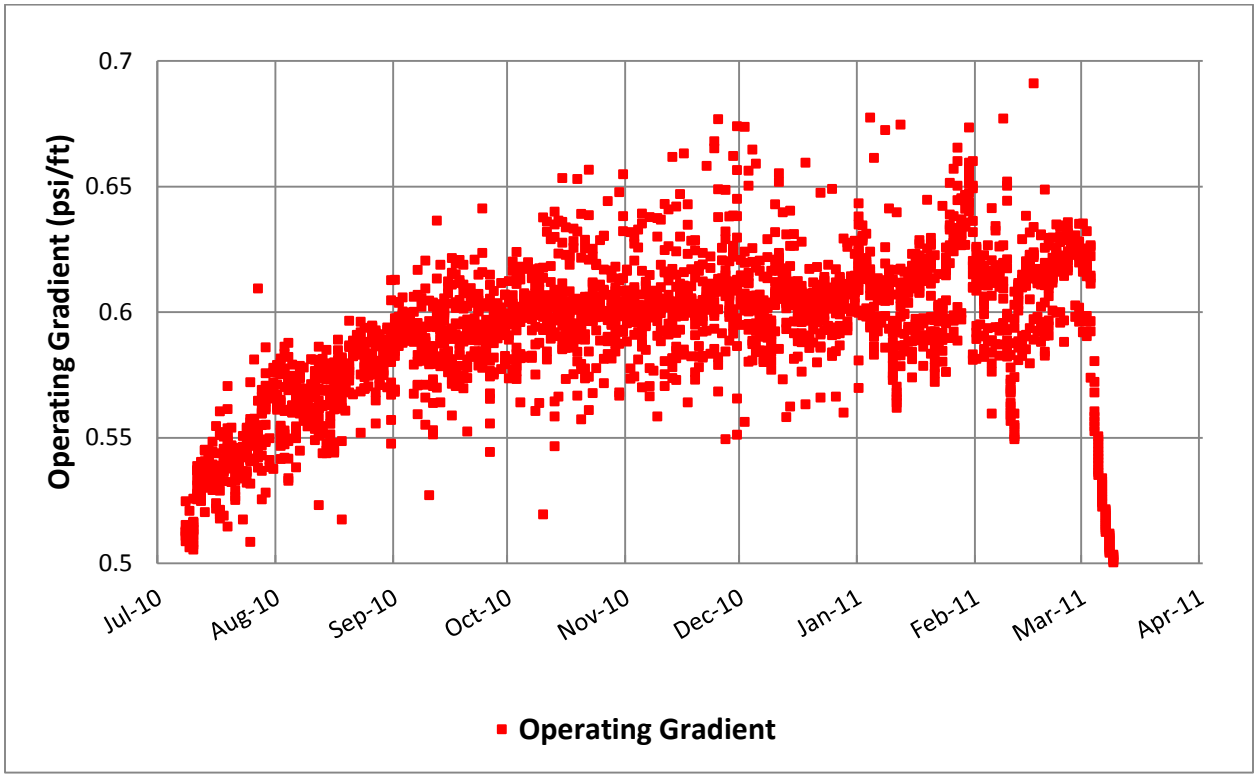


FIGURE F- 16: TRAMMEL OPERATING PRESSURE GRADIENT PLOT

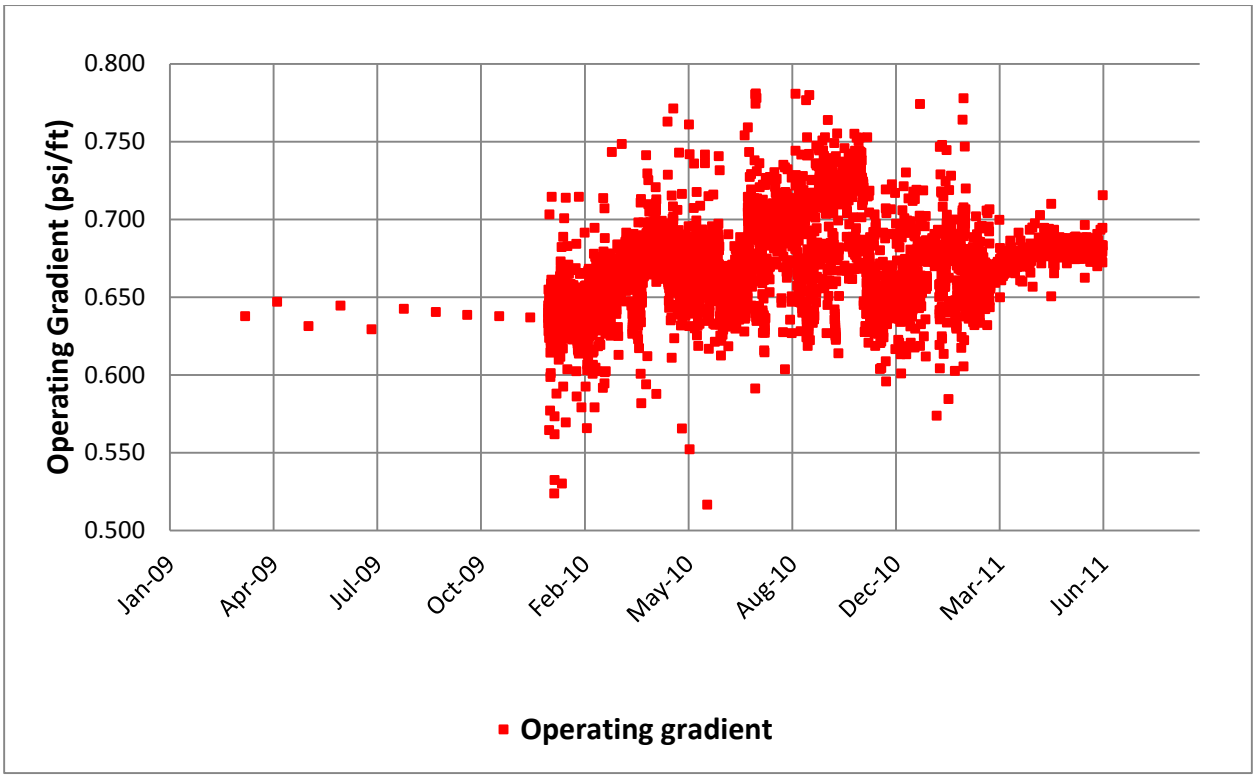


FIGURE F- 17: UNDERWOOD OPERATING PRESSURE GRADIENT PLOT

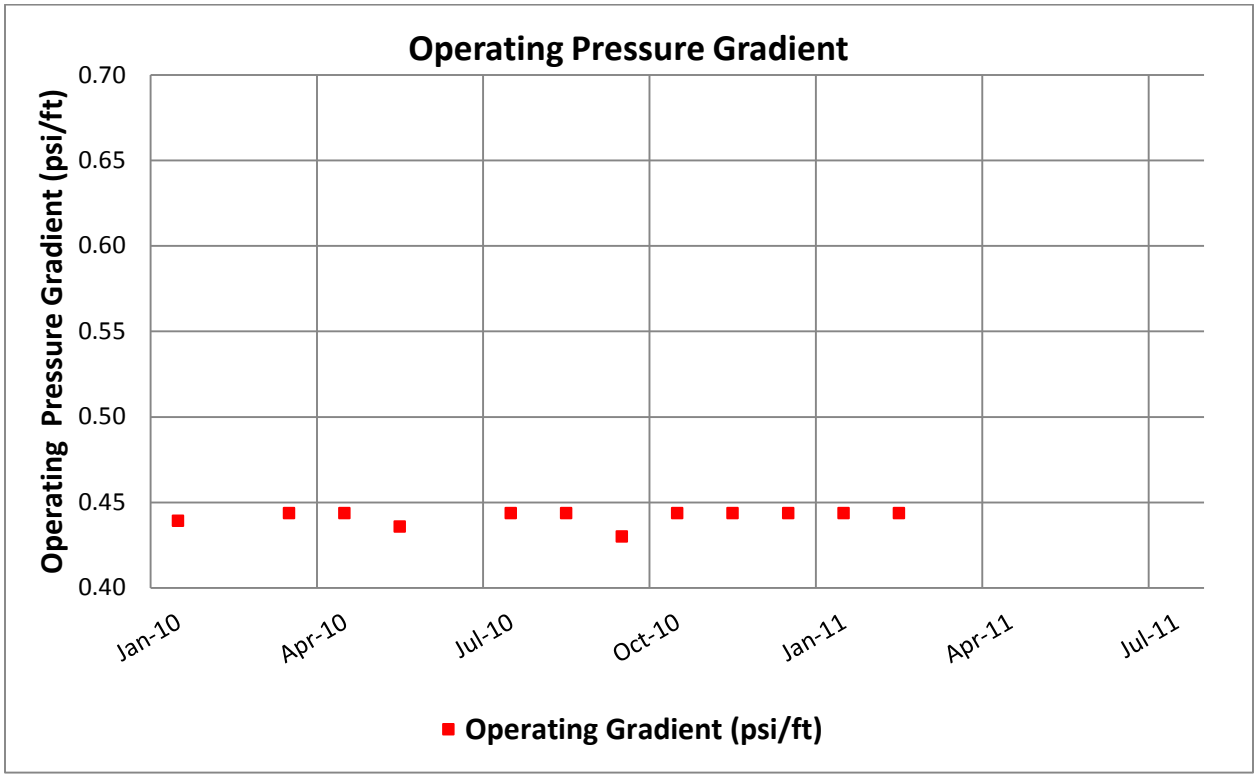


FIGURE F- 18: EDGMON OPERATING PRESSURE GRADIENT PLOT

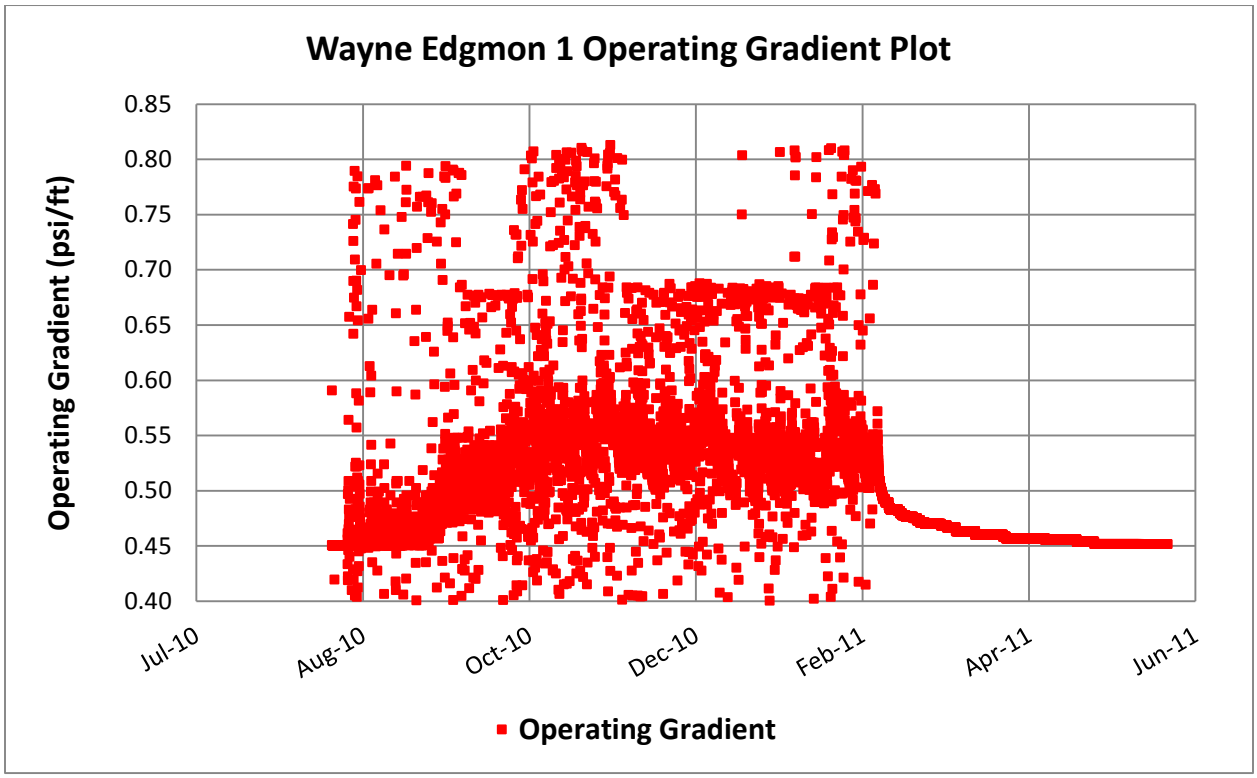


FIGURE F- 19: MOORE ESTATE TANDEM PLOT OF CUMULATIVE EARTHQUAKE EVENTS AND HALL INTEGRAL WITH DERIVATIVE

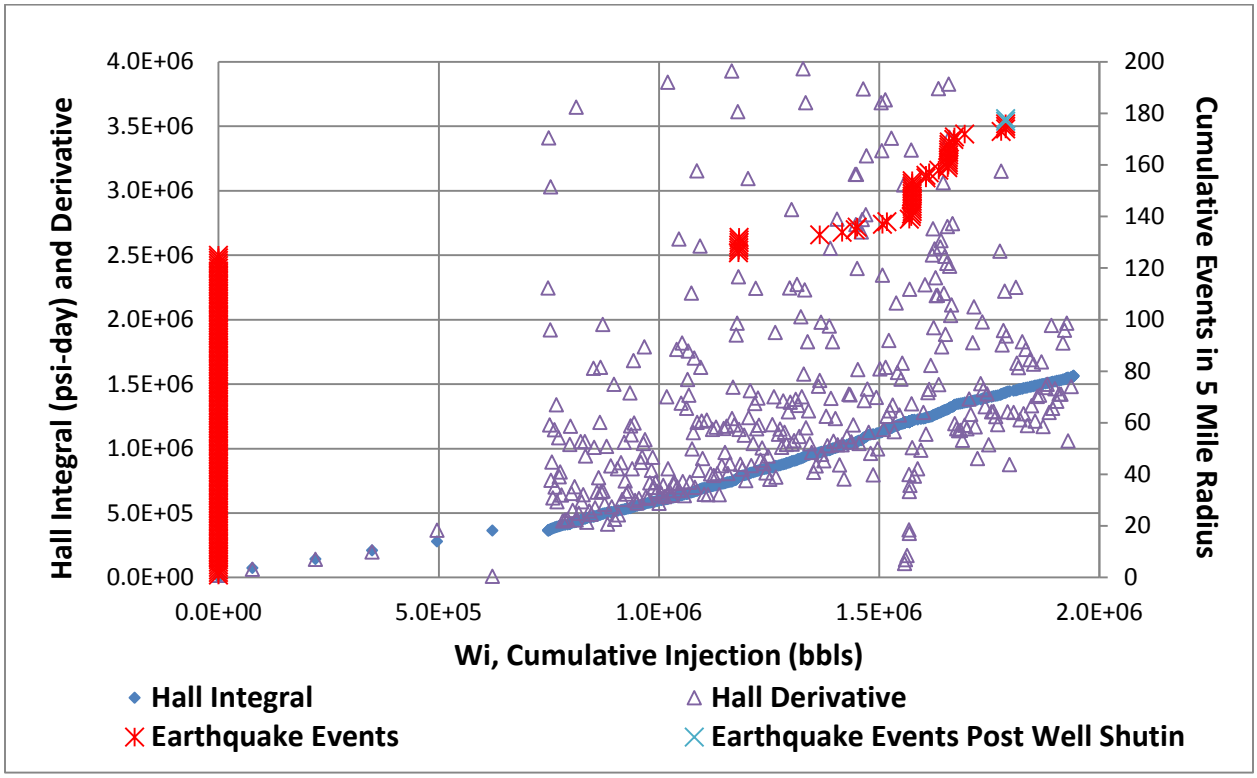


FIGURE F- 20: MOORE ESTATE TANDEM PLOT OF CUMULATIVE EARTHQUAKES SINCE 2010 AND HALL INTEGRAL

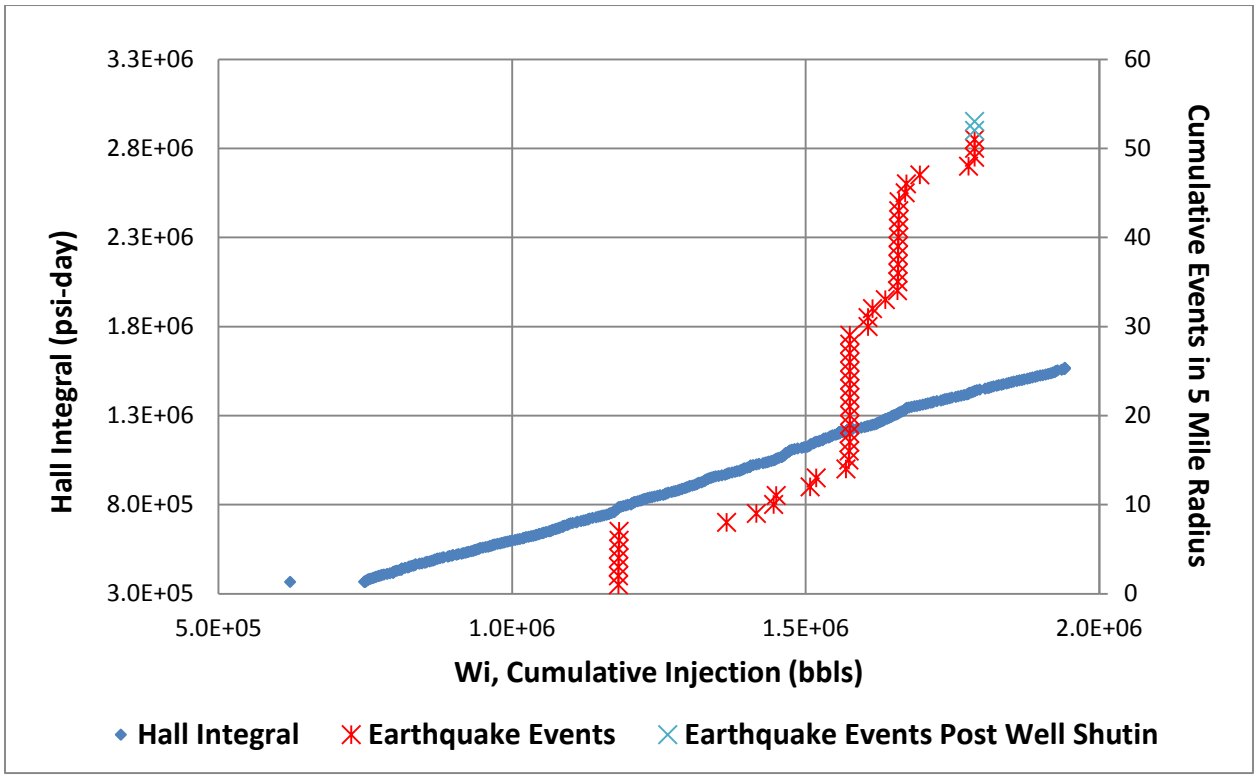


FIGURE F- 21: MOORE ESTATE ZOOMED TANDEM PLOT

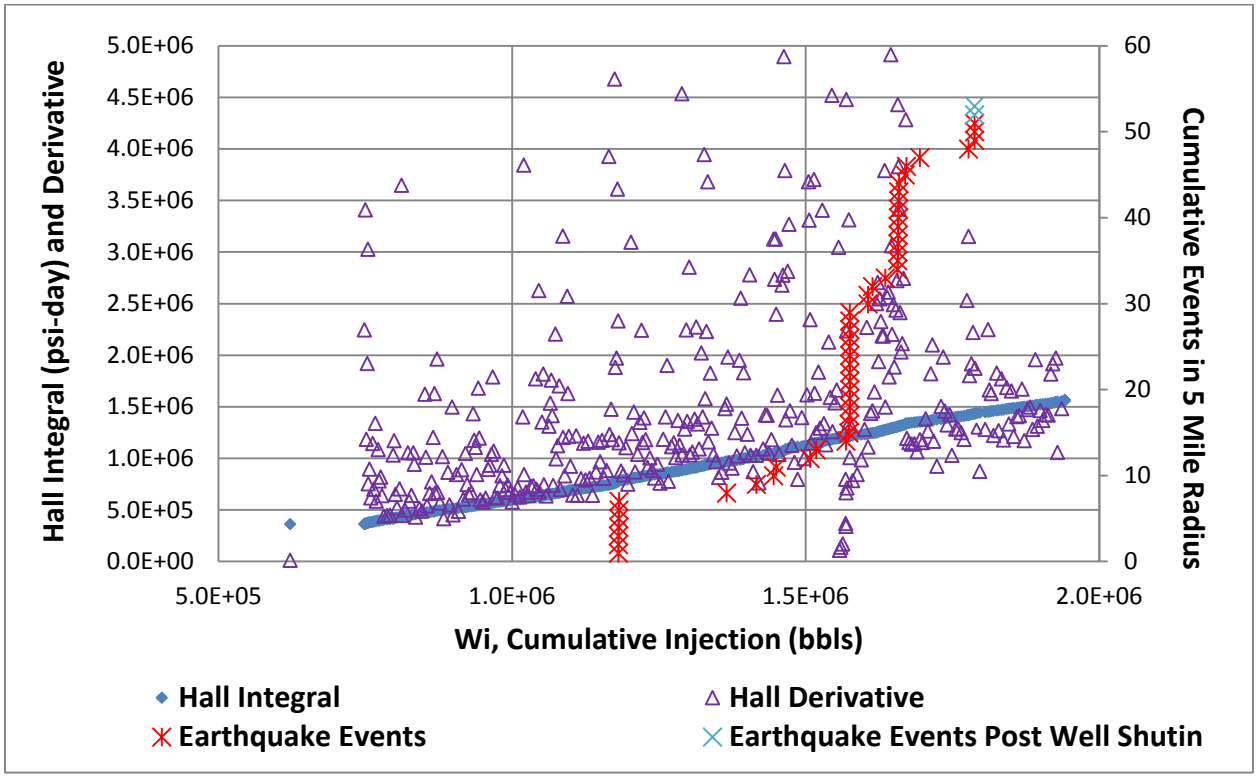


FIGURE F- 22: SRE TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

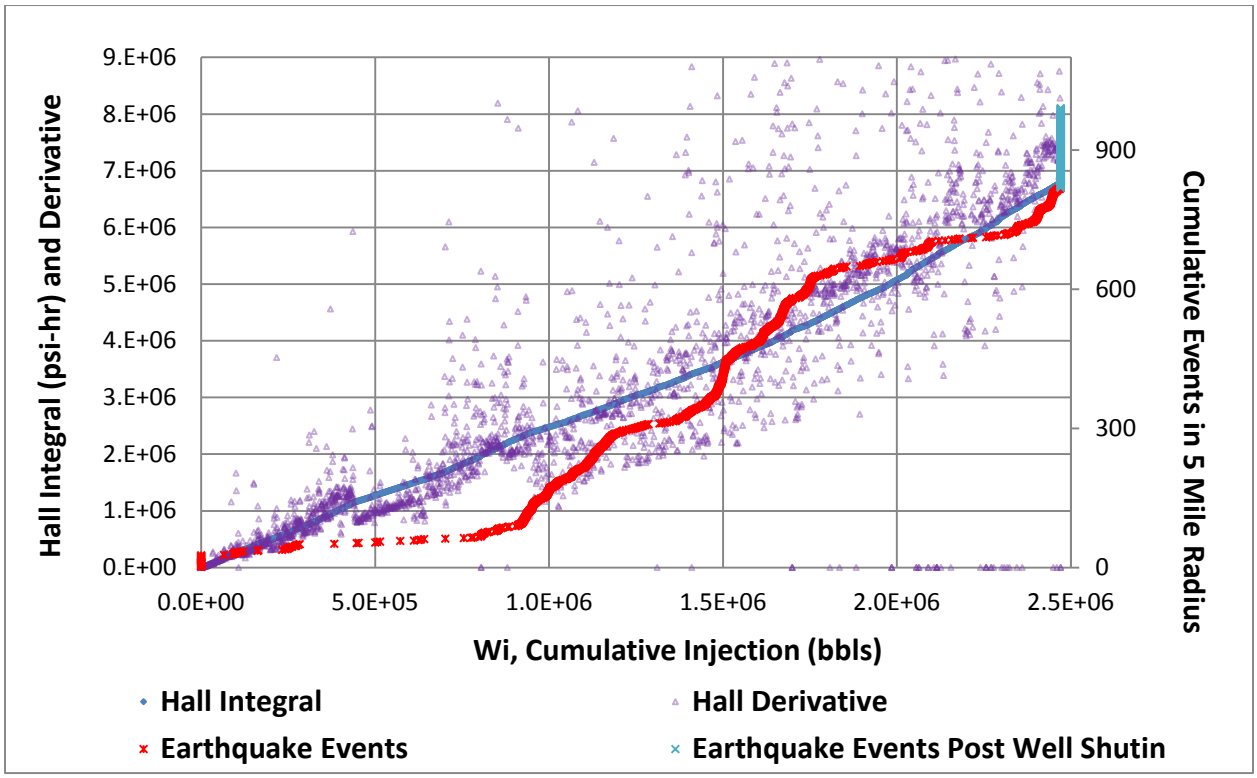


FIGURE F- 23: SRE ZOOMED TANDEM PLOT TO NOVEMBER 21, 2010

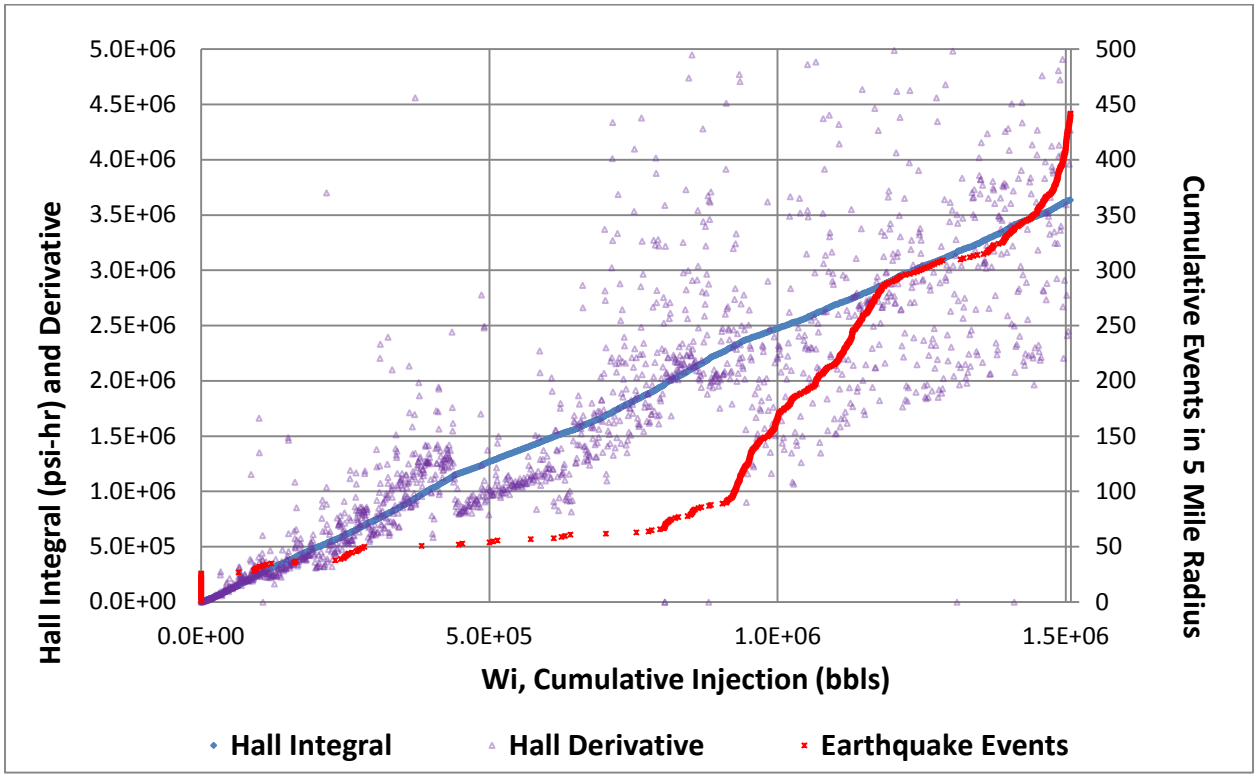


FIGURE F- 24: TRAMMEL TANDEM PLOT OF CUMULATIVE EARTHQUAKE EVENTS AND HALL INTEGRAL WITH DERIVATIVE

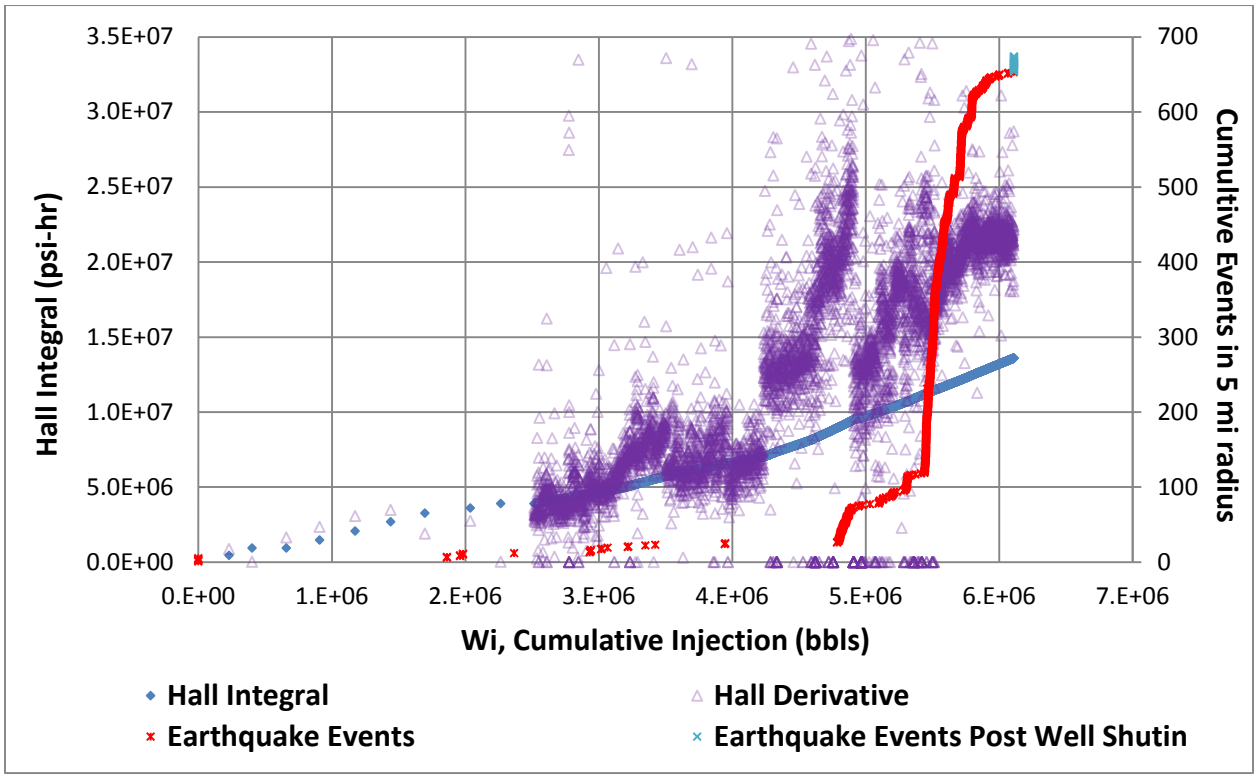


FIGURE F- 25: TRAMMEL TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL

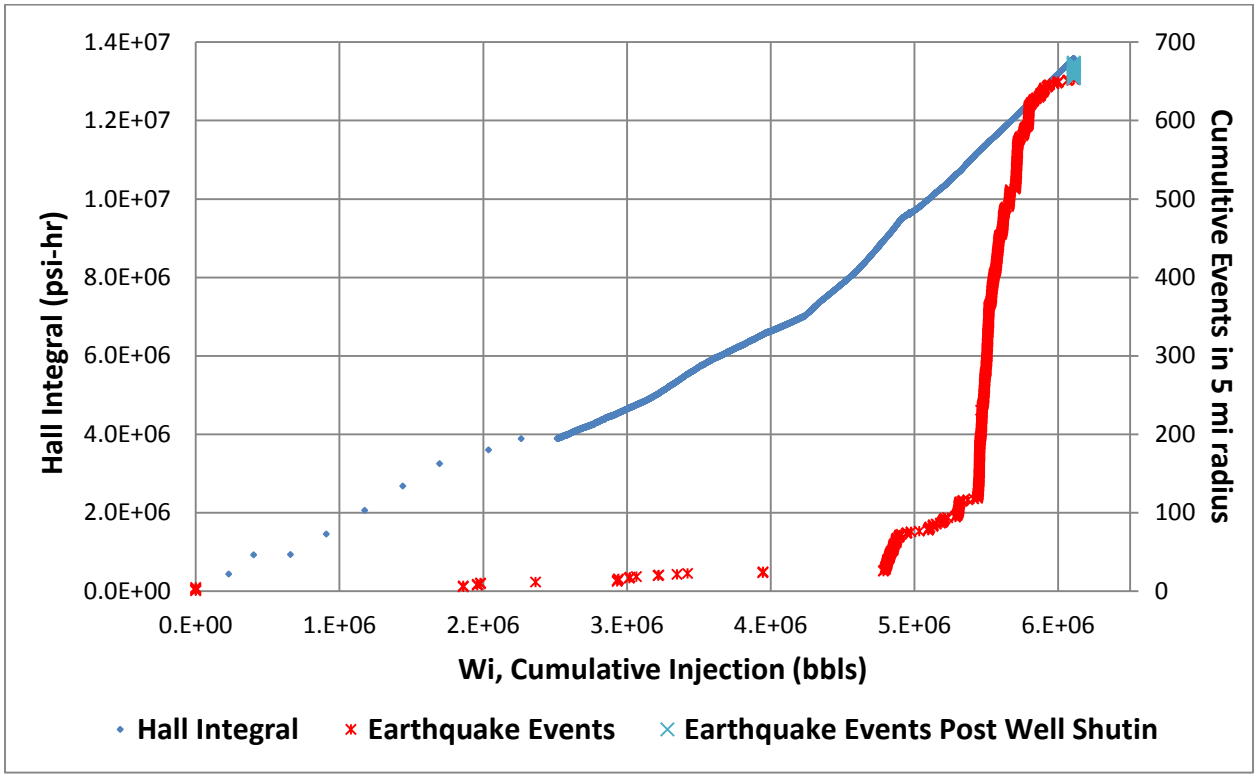


FIGURE F- 26: EDGMON TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

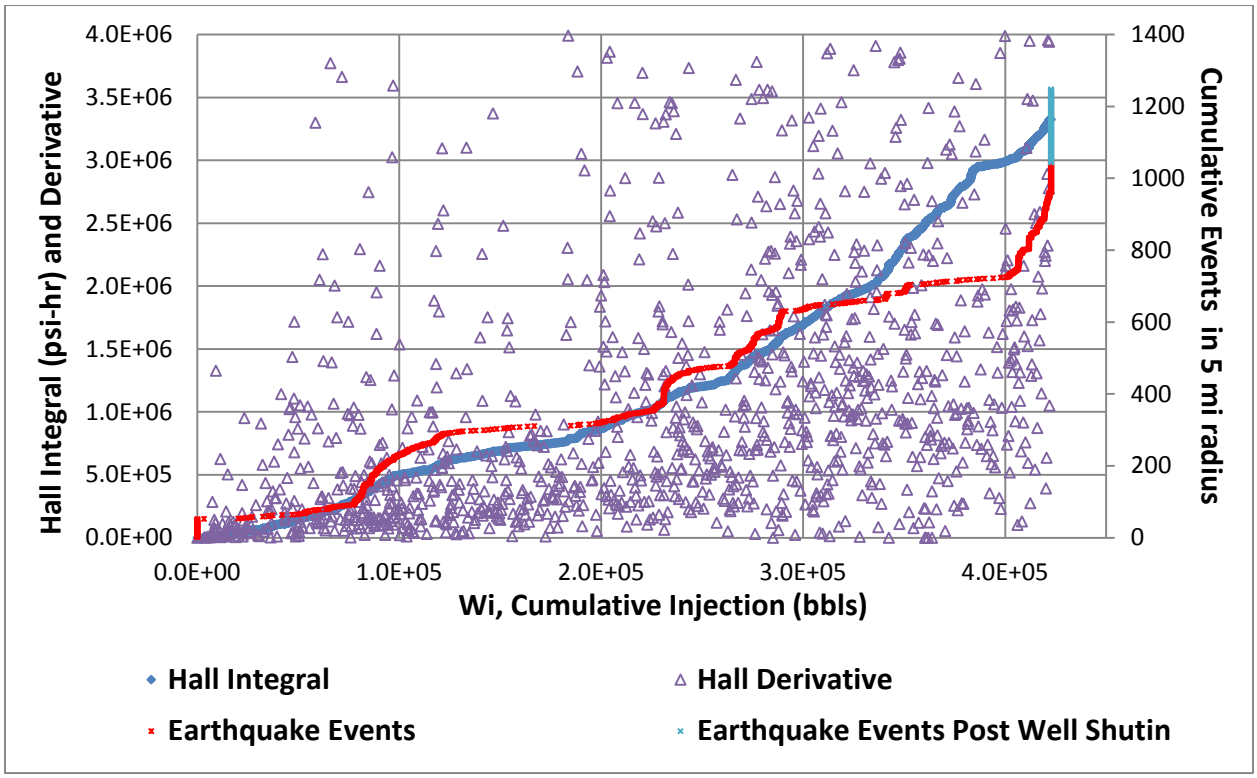


FIGURE F- 27: EDGMON TANDEM PLOT OF CUMULATIVE EARTHQUAKE EVENTS AND HALL INTEGRAL

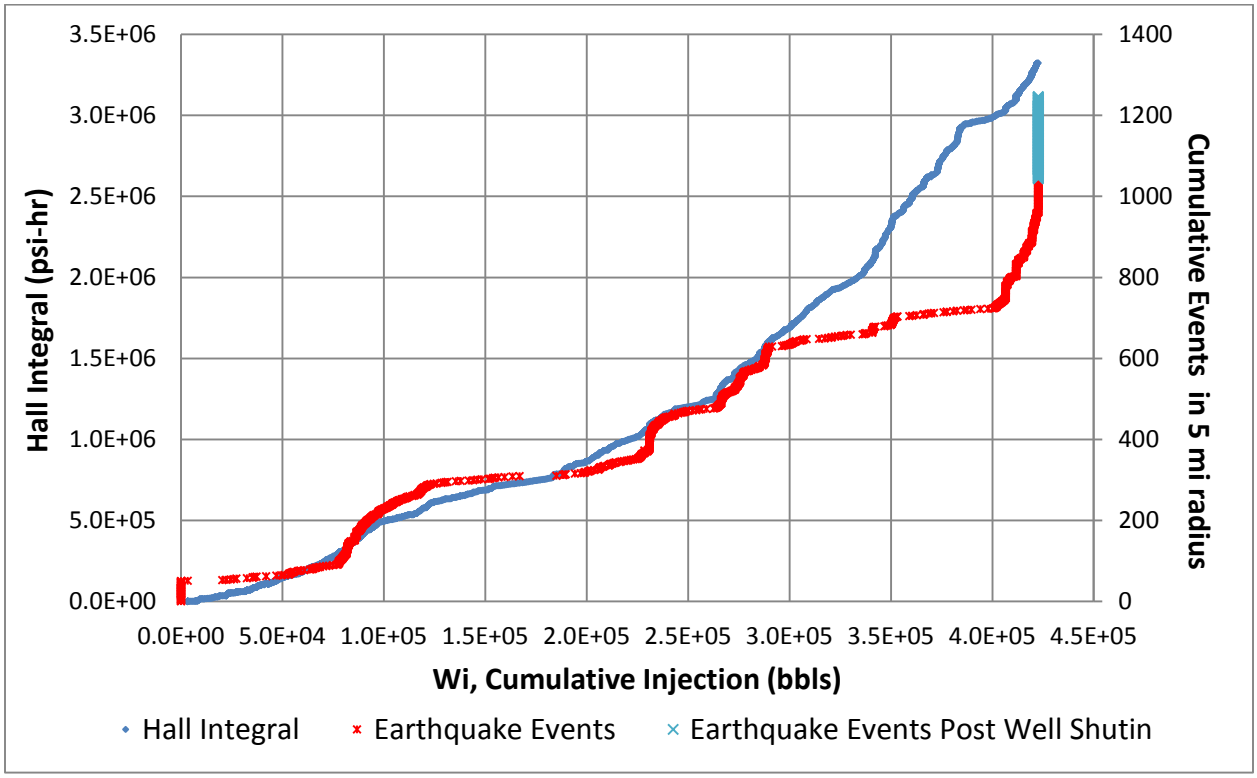


FIGURE F- 28: EDGMON ZOOMED TANDEM PLOT OF EARLY DATA TO DECEMBER 19, 2010

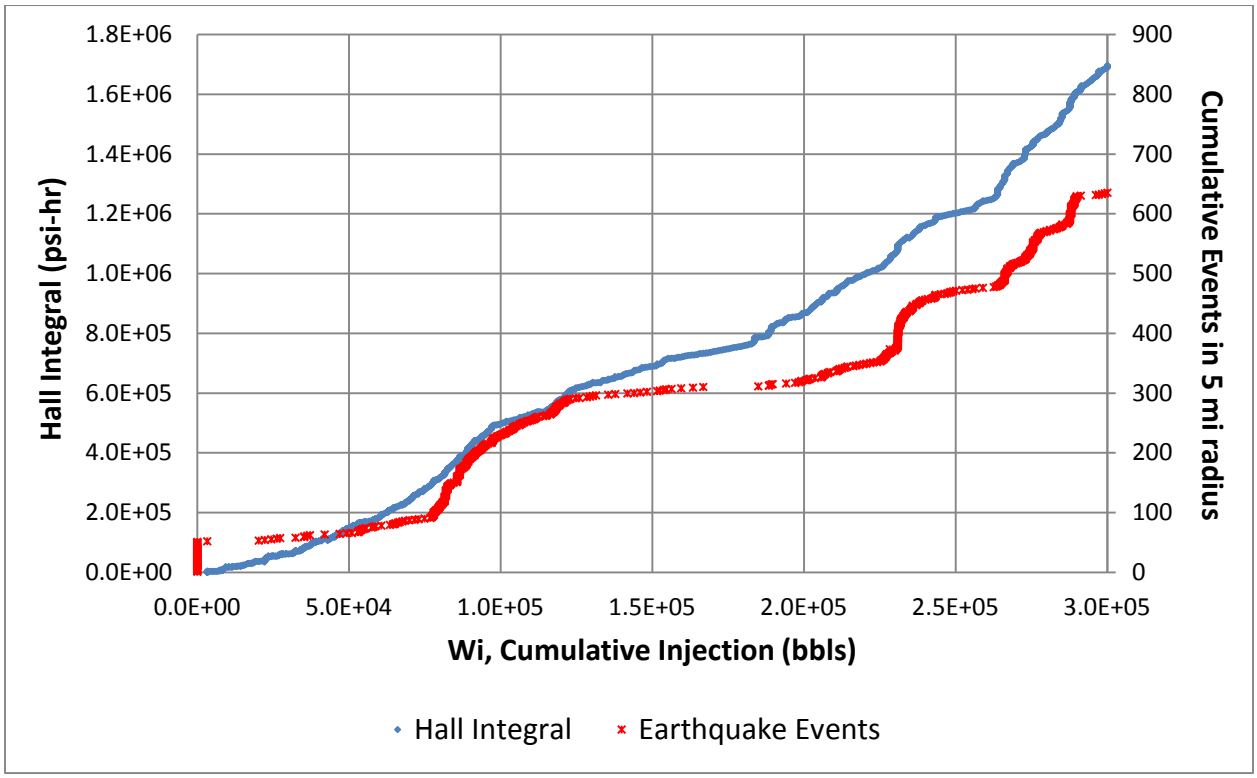


FIGURE F- 29: EDGMON STEP RATE TEST

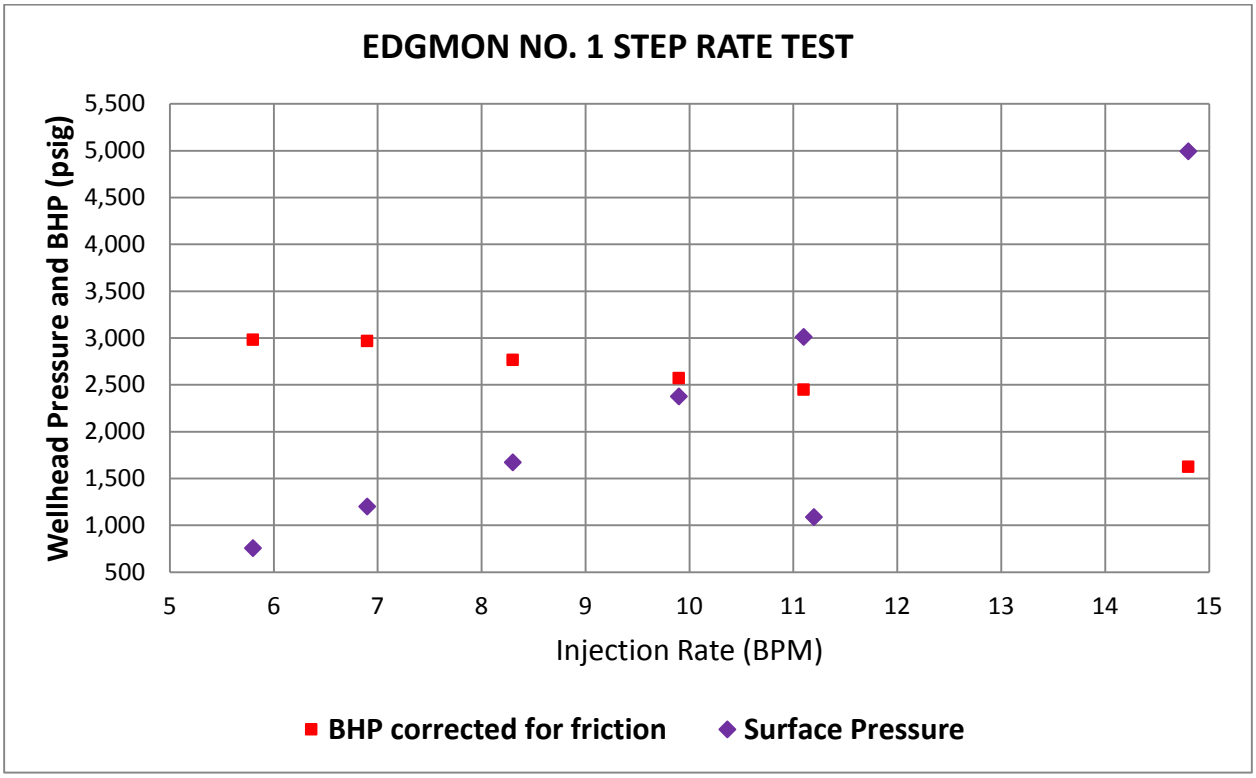


FIGURE F- 30: SRE LOG-LOG PLOT OF PRESSURE FALLOFF DURING FINAL SHUT-IN OF WELL

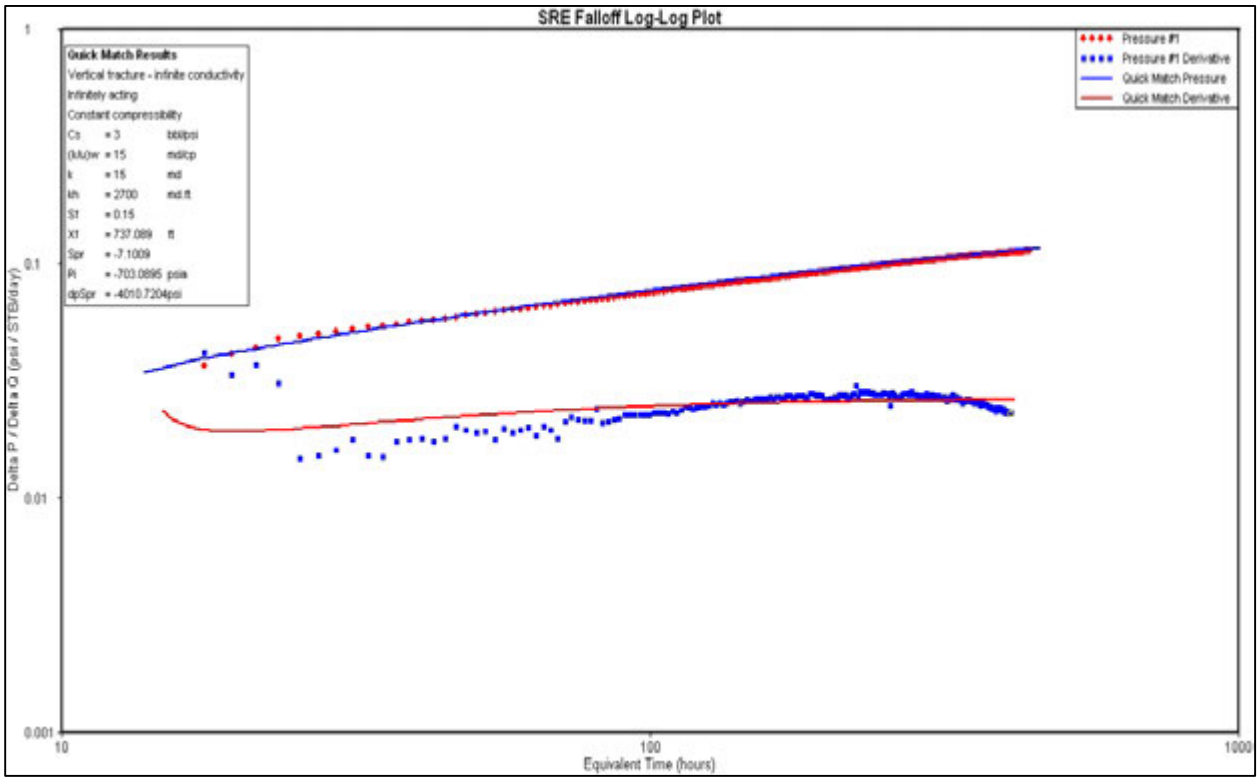


FIGURE F- 31: TRAMMEL LOG-LOG PLOT OF PRESSURE FALLOFF DURING FINAL SHUT-IN OF WELL

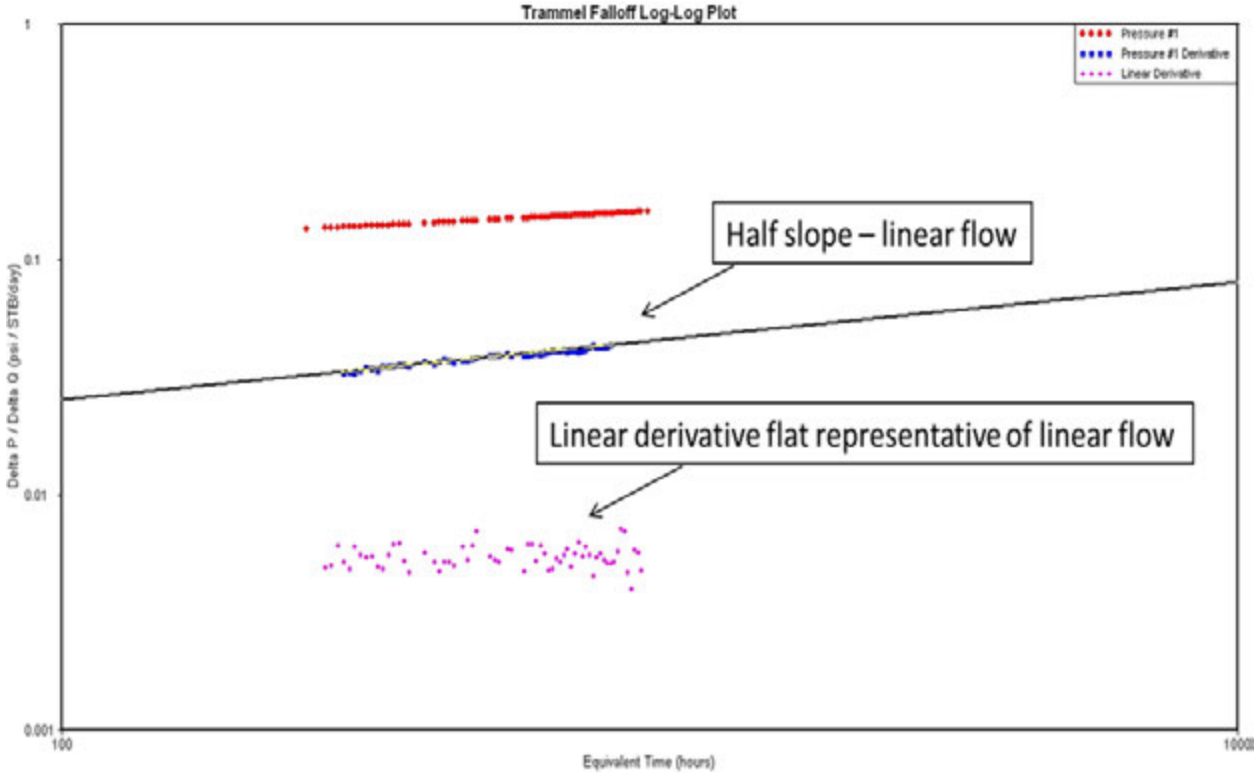
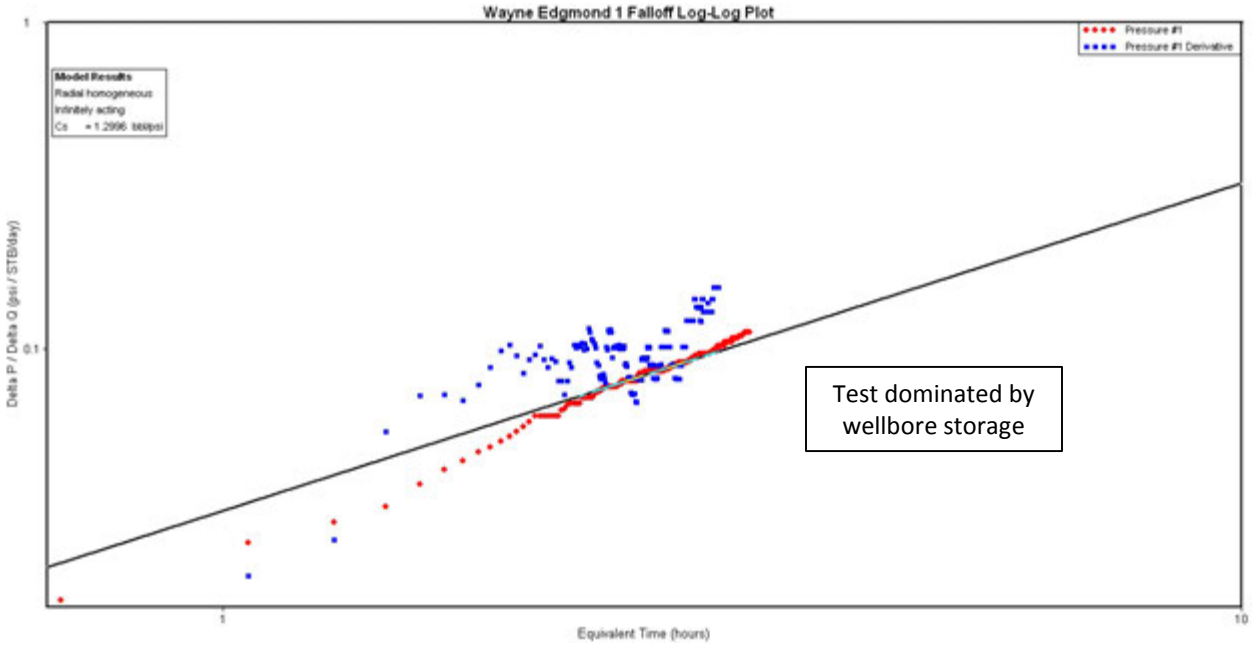


FIGURE F- 32: EDGMON LOG-LOG PLOT OF PRESSURE FALLOFF DURING FINAL SHUT-IN OF WELL



APPENDIX G: BRAXTON COUNTY, WEST VIRGINIA CASE STUDY AREA

Braxton, West Virginia, Case Study Background G-1
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All four case studies were considered in the development of the decision model. The state agencies' handling of these events was the basis for some of the approaches listed in the decision model described in APPENDIX B: . Consequently the Injection-Induced Seismicity Working Group (WG) elected to apply the decision model framework to the case study events. Following the decision model framework, the well in this case study falls under the existing well category. Increased earthquake frequency following the start of disposal operations raised concern.

BRAXTON, WEST VIRGINIA, CASE STUDY BACKGROUND

A series of minor earthquakes started in early 2010 around Braxton, West Virginia, a little over a year after disposal operations started in a relatively nearby well (Figure G-1). The relationship between the earthquakes and the Class II disposal well was investigated by the West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas.

To aid understanding of area site conditions, the geologic setting, existing oil and gas activity and seismic history are provided, followed by a description of the focused site assessment, which includes details on well operations.

Geologic Setting

Braxton County is located in the Appalachian basin, on the eastern edge of the Devonian Marcellus shale and Trenton limestone gas plays (Figure G-1). The Marcellus outcrops in eastern West Virginia, though this is not shown in Figure G-1 (Avary, 2011).

The Marcellus unconformably overlies the Onondaga Limestone (Figure G-2) (Avary, 2011) and Figure G-3 (WVGES, 2011), which is an easily recognizable marker on logs and seismic surveys. The Marcellus is predominantly siliceous, with mixed muscovite and illite and minor amounts of pyrite and kaolinite (Boyce and Carr, 2009).

Oil and Gas Activity

Gas production in the Marcellus shale of West Virginia started in 2005, with Braxton County drilling starting in 2006. The Elk Valley (626407) Class II wastewater disposal well was initially completed in the Marcellus shale as a gas production well. The vertical well was later converted to a disposal well in the same interval.

History of Seismicity

West Virginia has a history of seismicity along the Ohio border and along the southeast border with Virginia. However, prior to the seismic events that started in 2010, only one low level earthquake, which occurred in 2000, was recorded in the USGS Advanced National Seismic System (ANSS) database in West Virginia. The seismicity search for this case study used a number of databases including ANSS, Eastern, Central & Mountain States NEIC Earthquake database (SRA), Central and Eastern United States CERI Earthquake database (NCEER), Significant U.S. quakes, NEIC Earthquake database (USHIS), Center for Earthquake Research and Information (CERI) and Preliminary Determination Earthquake, NEIC Earthquake database (PDE).

Focused Site Assessment

There is only one disposal well in the general vicinity of the earthquakes. Injection activities began in the Elk Valley disposal well in March 2009, about one year prior to the start of seismic events. Based on earthquake activity and the regional seismometer network capabilities, an arbitrary 12 mile (19 km) radius was selected to define the focus area around the well, Figure G-4.

Information Collected

Data for this case study well was collected from the WVDEP Office of Oil and Gas. Permitting documents provided details concerning completion depths, construction information, and permit conditions. Operational monitoring reports provided monthly injection volumes, maximum injecting tubing pressure, maximum shut-in tubing pressure, and hours operated during the month.

Disposal Well in Case Study

Permit, construction and completion information for the Elk Valley well are summarized below:

TABLE G-1: ELK VALLEY DISPOSAL WELL PERMIT CONDITIONS

UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation
2D0072539	no	2,100	N/A	Marcellus, fractured

TABLE G-2: ELK VALLEY DISPOSAL WELL COMPLETION DATA

Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
6,472	6,524	6,556	5½ " at 6,543'	2 7/8" at 6,395'

DEPTHS ARE MEASURED DEPTH IN FEET, NOT TVD

TABLE G-3: ELK VALLEY DISPOSAL WELL OPERATIONS

Initial Disposal	Final Disposal	Plugged and Abandoned	Comments
Mar 2009			Operating

Permit information indicated that the vertical well was initially fractured with a total of 355,000 pounds of sand and 14,398 barrels of water prior to being converted to a disposal well.

The chlorides in the fluid analysis included in the permitting documentation ranged from 0–250,000 mg/L.

Additional Geosciences Information

A summary of the recent focus area earthquakes, within a 12 mile (19 km) radius[29] of the Braxton County case study well is provided in the Table G-4 below and a timeline of recent events is shown on Figure G-5. A zoomed map area of the disposal well and earthquake activity is included on Figure G-4.

TABLE G-4: BRAXTON, WEST VIRGINIA, FOCUS AREA SEISMICITY THROUGH SEPTEMBER 30, 2013

Year	Starting Date	Number of Events	Magnitude			Ending Date
			Min.	Avg.	Max.	
2010	4/4/2010	8	2.2	2.6	3.4	7/25/2010
2011		0				
2012	1/10/2012	1		2.8		1/10/2012
2013	3/31/2013	3	2.6	2.9	3.4	8/16/2013

Operational Data

The Elk Valley disposal well had monthly operating data available from the WVDEP. Monthly data included maximum and shut-in tubing pressures, total monthly injection volume, and hours operated, which were used to convert the monthly injection volume to an average injection rate. The operating surface pressure was assumed to be the average of the maximum injection and maximum shut-in pressures for each month. Surface pressures were converted to approximate bottomhole pressures (BHPs) at 6,395 feet. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 100 for steel tubing was used to limit the friction pressure loss. BHPs were calculated by adding the surface pressure and pressure of the hydrostatic column of fluid and subtracting the calculated friction pressure loss. A specific gravity of 1.125 was used to approximate 100,000 ppm chloride brine. The hydrostatic column of fluid was calculated at 3,115 psia. Because the well went on a vacuum, an average static reservoir pressure of 2800 psia was assumed for the Hall integral calculation.

Petroleum Engineering Review

Operational Analysis

Three operating data-related plots were prepared including an operational data overview plot (Figure G-6), a monthly operating pressure gradient plot (Figure G-7), and tandem plots of

[29] The search area was increased owing to the uncertainty in the event location, occasioned by the poor density of seismometers.

cumulative seismic events and the Hall integral with derivative, based on the calculated average tubing pressures, plotted against cumulative water injection (Figure G-8 and G-9).

The monthly hours reported indicated that the well did not operate continually throughout each month. The Hall integral and derivative functions were prepared as continuous functions from monthly data, and only the hours operated in each month were used in the calculation of the Hall integral and derivative functions. To determine if the earthquake cumulative event trend corresponded to the Hall integral trend, a tandem plot of both cumulative earthquake events and the Hall integral with derivative response versus cumulative water injection was prepared for the Elk Valley disposal well, as shown in Figure G-8. Figure G-9 also shows an expanded view of the tandem plot responses early in the operational life of the injection well.

- Operational overview plot (Figure G-6)
    - Last quarter 2010 had higher injection volumes with lower pressures
- Operating pressure gradient (Figure G-7)
- Tandem plot of Hall integral with derivative and cumulative seismicity events (Figures G-8 and G-9)
    - Hall integral with derivative upswing response during late portion of operational data, with corresponding seismicity events
    - Zoomed tandem plot
        - Slight separation between Hall integral and derivative at seismic events early in operating life of the well

Pressure Transient Analysis

A step rate test was performed on the Elk Valley disposal well in March 2008, prior to the start of injection and was included with the permit information. The injection rate started at 0.5 and increased to 5.5 barrels per minute over eight rate steps. Individual steps were primarily 30 minute intervals, except for the last step held for 3 hours. A total of 1,410 barrels was injected into the well during 6.5 hours of step rate testing. A summary of the rate and tubing pressure measurements is included in Table G-5.

TABLE G-5: MARCH 2008 STEP RATE TEST DATA

Injection Tubing Pressure at the End of Each Rate Step (psig)	Average Constant Injection Rate for Rate Step (BPM)
150	0.5
0	1.0
0	1.5
0	2.0

Injection Tubing Pressure at the End of Each Rate Step (psig)	Average Constant Injection Rate for Rate Step (BPM)
400	3.0
1,160	4.0
1,750	5.0
1,900	5.5

A linear plot of the 2008 step rate test data is shown in Figure G-10. The linear plot is the final injection pressure at the end of each rate step versus the injection rate for the same rate step. Electronic data for the step rate test were not available, so a log-log plot analysis of each individual injectivity test was not possible. The well went on a vacuum following the first rate step. Pressures increased to nearly 2,000 psi after positive pressures were reestablished during the fifth rate step.

Step rate test (Figure G-10)

- Linear plot indicated a slope break between the sixth and seventh rate steps of 4 and 5 BPM
    - Suggested a fracture extension surface pressure of roughly 1,650 psi
    - Value would suggest a fracture gradient of approximately 0.75 psi/foot

The Hall plot showed several slope breaks suggesting increased difficulty of injection. The calculated operating gradient in Figure G-7 showed operating gradients under 0.75 psi/foot, below the fracture extension gradient indicated by the step rate test linear plot.

Summary of Engineering Analysis

The sole West Virginia case study disposal well, Elk Valley, had only one step rate test with marginal quality surface pressure data, indicating a fracture gradient of 0.75 psi/foot. The operating gradient plot indicated that the well operated below its estimated fracture gradient. The Elk Valley tandem plot, Figure G-8, showed a very pronounced extended upswing in both the Hall integral and derivative responses. The upswing plot indicates a strong increase in difficulty of injectivity as time went on and suggests an area boundary may have been encountered. An early cluster of seismic events occurred on the tandem plot while the well's Hall responses indicated only radial flow. Four later seismic events did occur long after the well established its pronounced trend of increasingly difficult injection.

Actions Taken by UIC Regulatory Agency in Braxton County, WV Area

In response to the seismic activity starting in April 2010, the West Virginia Department of Environmental Protection Office of Oil and Gas (WVDEP) reduced the maximum allowable monthly injection volume in the Elk Valley disposal well.

Braxton County Area Multidisciplinary Integration of Findings

The single case study disposal well was completed into the Marcellus shale with a medium-scale hydraulic fracture stimulation. In general, very little detailed information was available on the fracture program. No fracturing data were available to assess the effective fracture length. However, given that the disposal zone is a shale formation beyond the stimulated portion of the reservoir, the permeability would likely be very low. The well's long term hydraulic response, based on the tandem plot analysis, indicates that a reservoir boundary (or boundaries) was encountered, such as a fault, a pinch out, or possibly the limits of fracture stimulation (effectively the limits of permeable rock).

Braxton Lessons Learned

- Initiating dialogue with the operator can result in early voluntary action, including acquisition of additional site data.
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.
    - Upswing in Hall integral and derivative plot may indicate a no-flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance.
- Engaging external geophysical expertise may bring a more accurate location (x,y,z) of the active fault and stress regime through reinterpretation or increased seismic monitoring.
- Additional seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
    - Epicenters of recorded events are scattered, due to an insufficient number of stations in proximity to the activity.
- A multidisciplinary approach can minimize and manage induced seismicity at a given location.
- Director discretionary authority can be used to solve site-specific concerns:
    - The Director acquired additional site information, requested action from operators.
        - WVDEP decreased allowable injection rates and total monthly volumes in response to seismic activity.

CITATIONS

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Avary, K. L., 2011, Overview of gas and oil resources in West Virginia: West Virginia Geological & Economic Survey.

Boyce, M. L., and T. R. Carr, 2009, Lithostratigraphy and petrophysics of the Devonian Marcellus interval in West Virginia and southwestern Pennsylvania: Morgantown, West Virginia University, p. 25.

NCEER: http://folkworm.ceri.memphis.edu/catalogs/html/cat_nceer.html

NEIC: <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>.

SRA and USHIS: <http://earthquake.usgs.gov/regional/neic/>.

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FIGURE G- 1: BRAXTON, WEST VIRGINIA CASE STUDY REGIONAL AREA

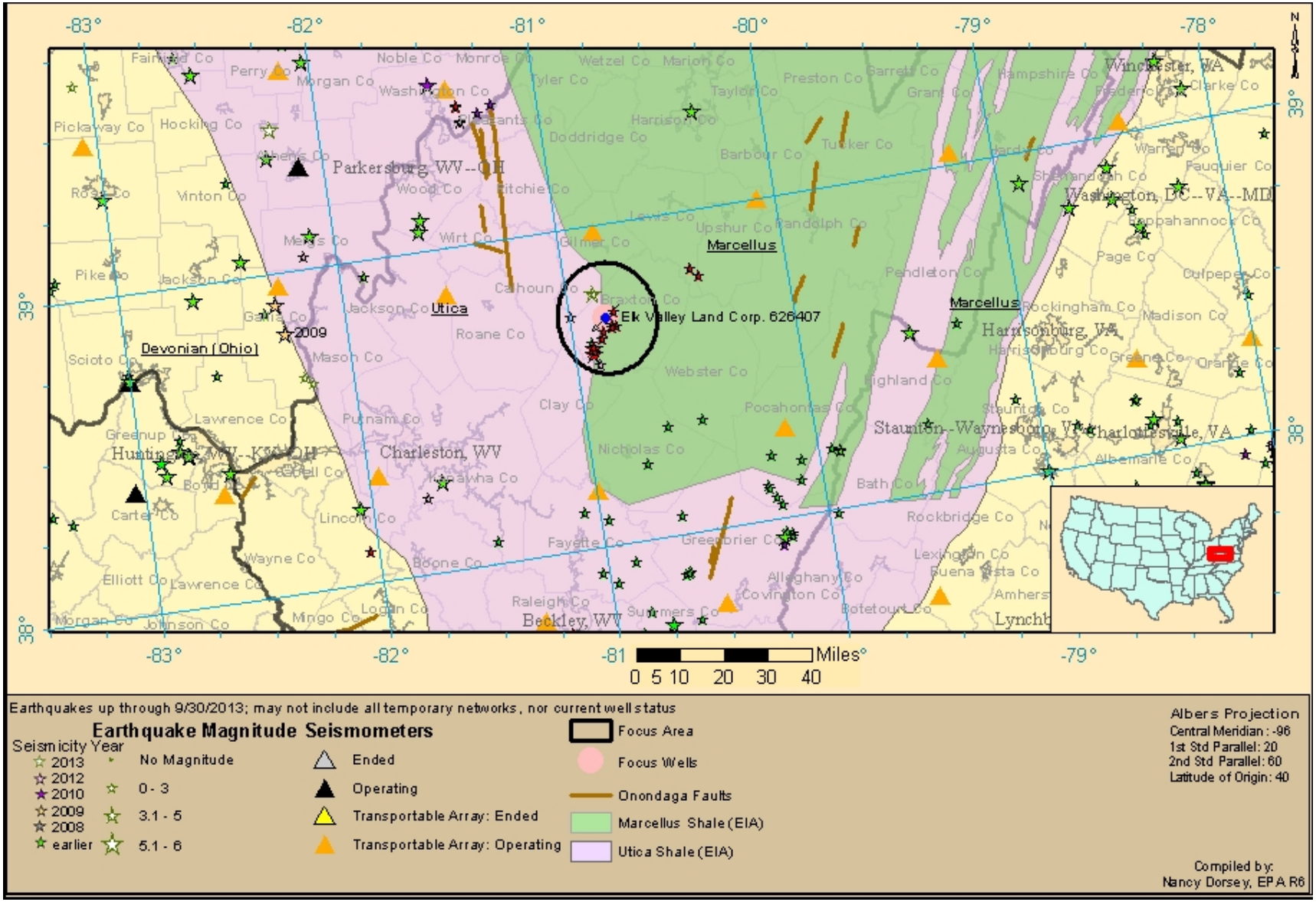


FIGURE G- 2: WEST VIRGINIA NOMENCLATURE (AVERY, 2011)

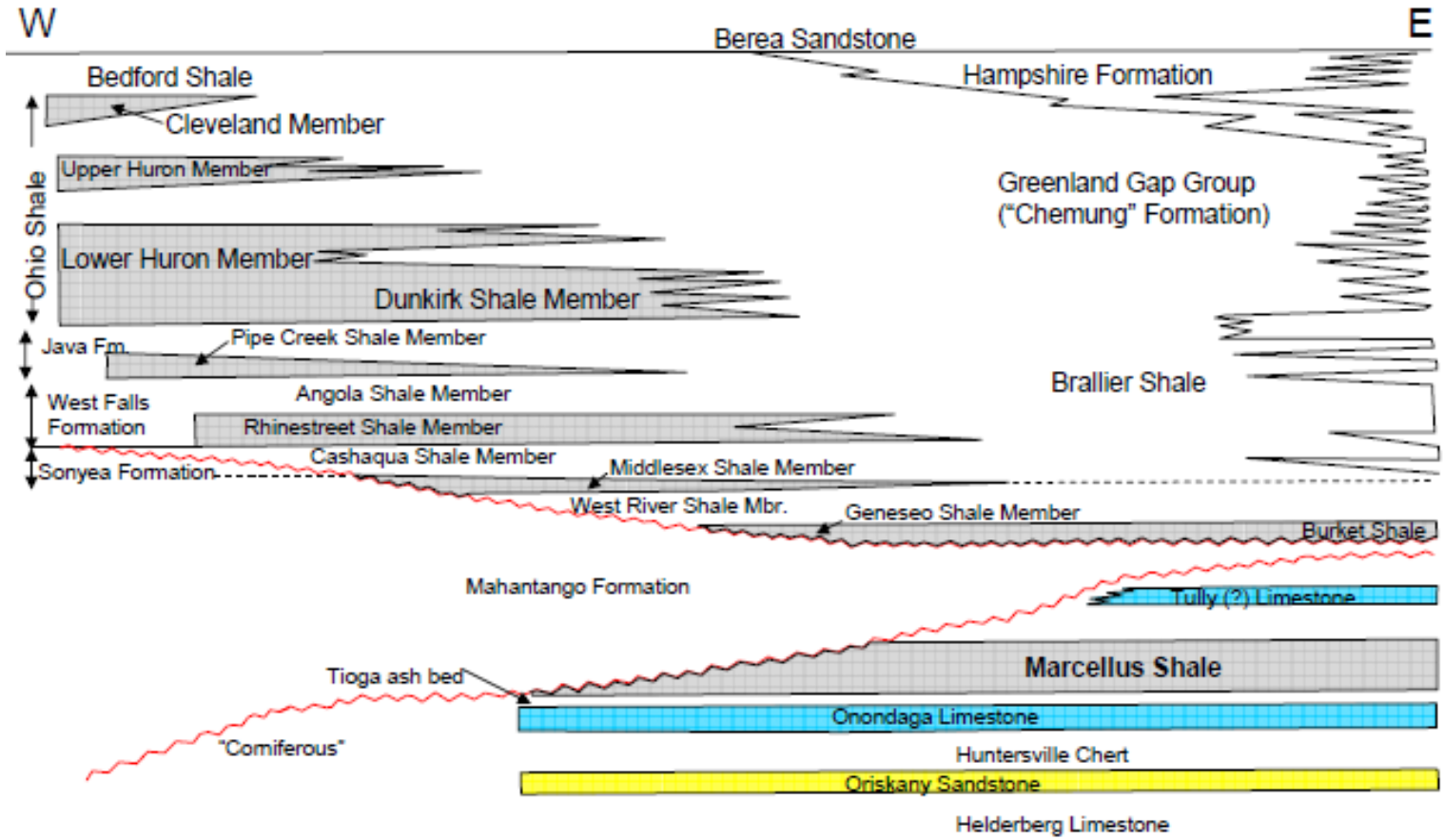


FIGURE G- 3: WEST VIRGINIA STRATIGRAPHIC COLULMN (UNPUBLISHED WVGES INFORMATION, 2011)

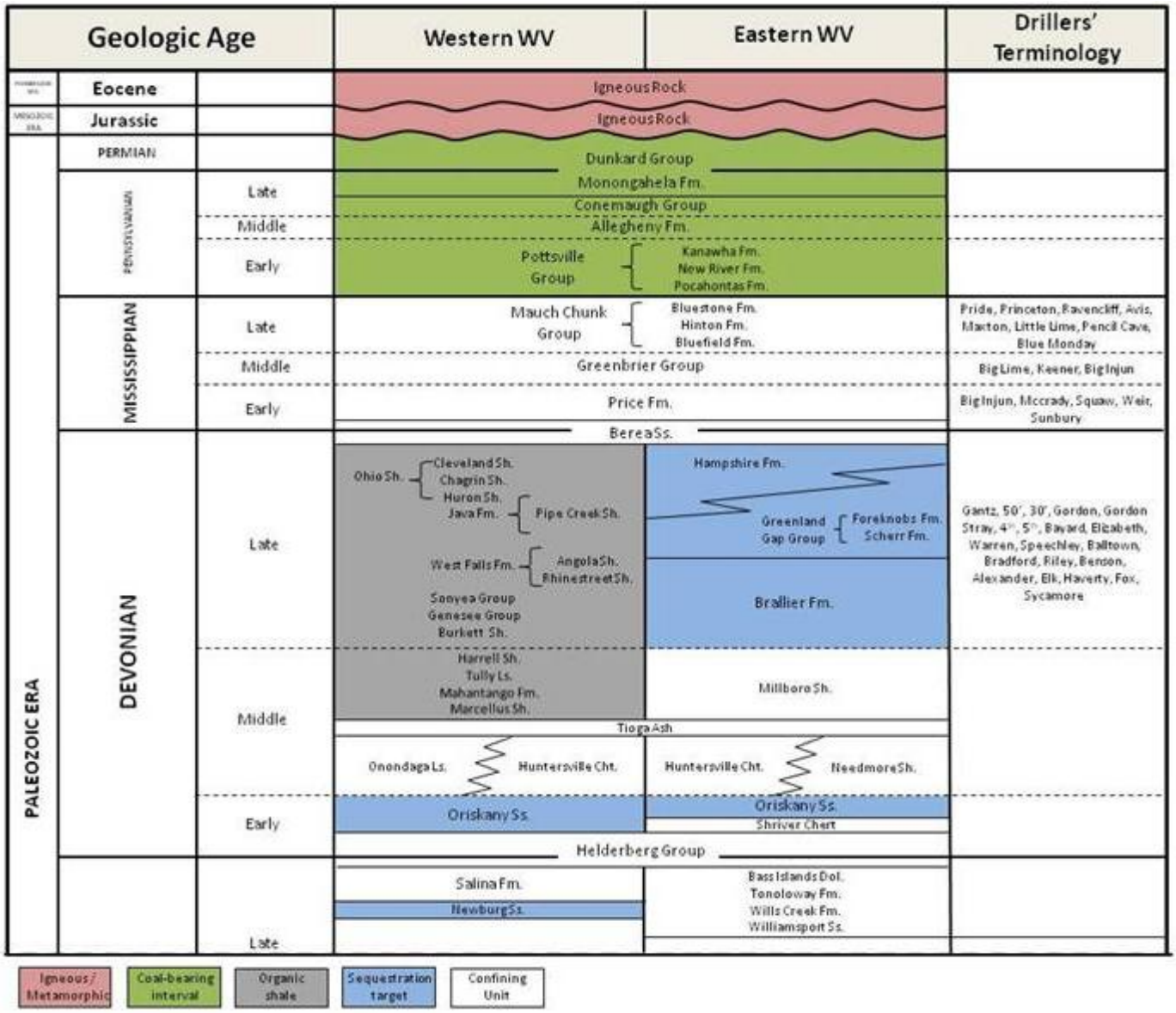


FIGURE G- 4: BRAXTON FOCUS AREA SEISMICITY MAP

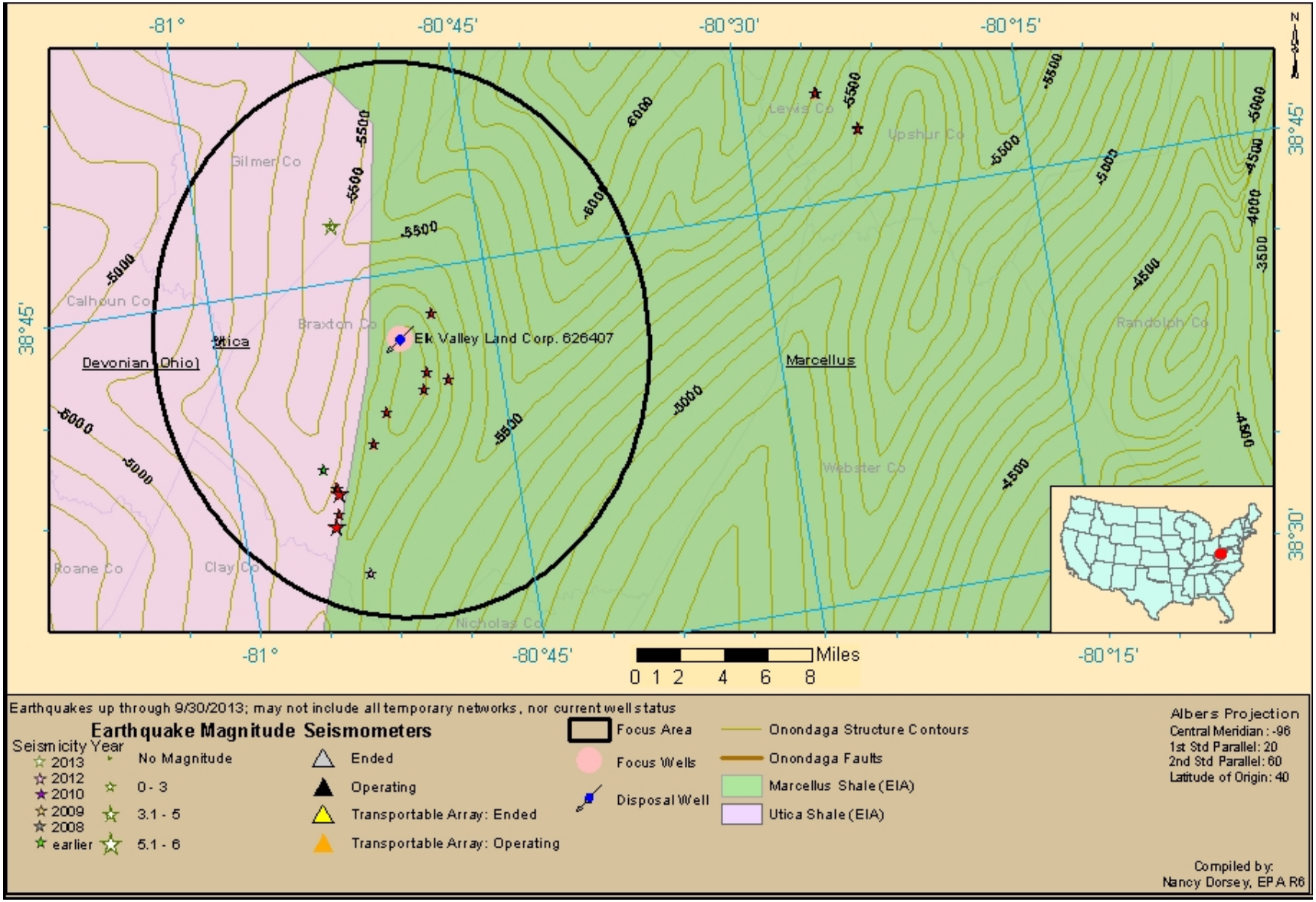


FIGURE G- 5: BRAXTON WEST VIRGINIA FOCUS AREA SEISMICITY TIMELINE

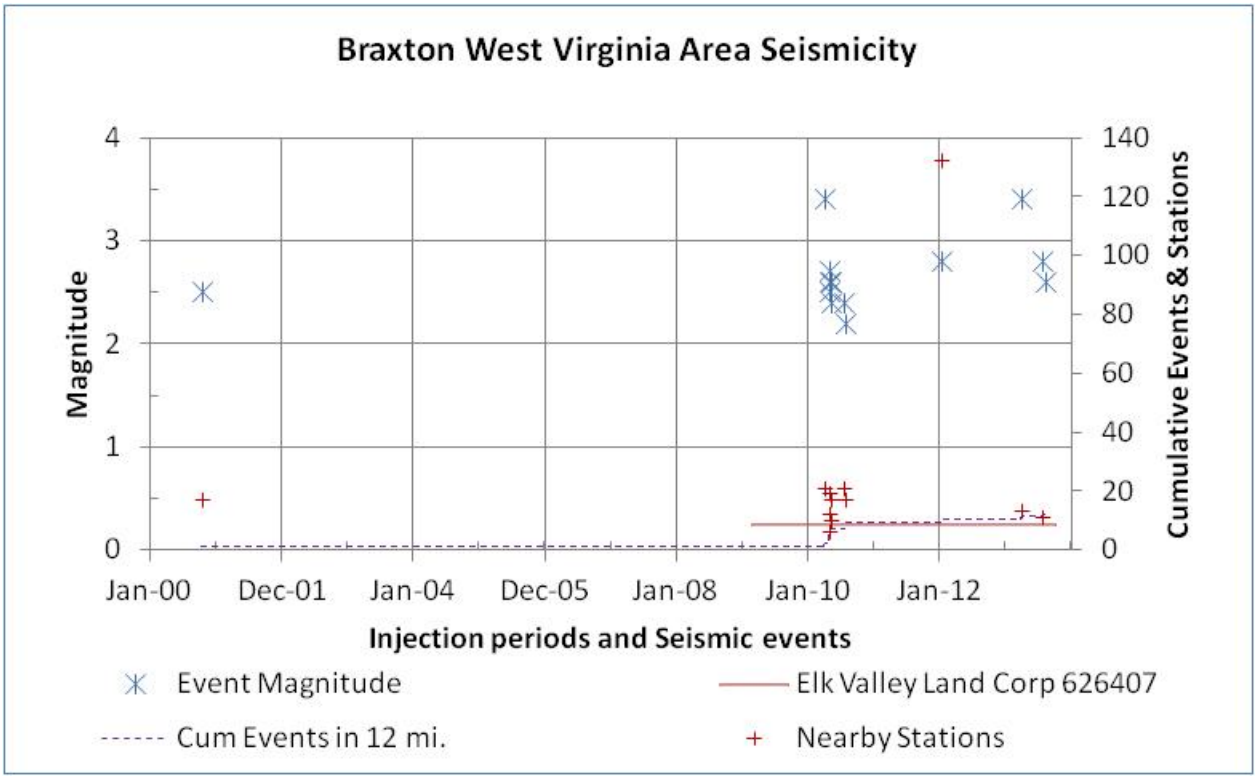


FIGURE G- 6: ELK VALLEY OPERATIONAL DATA PLOT

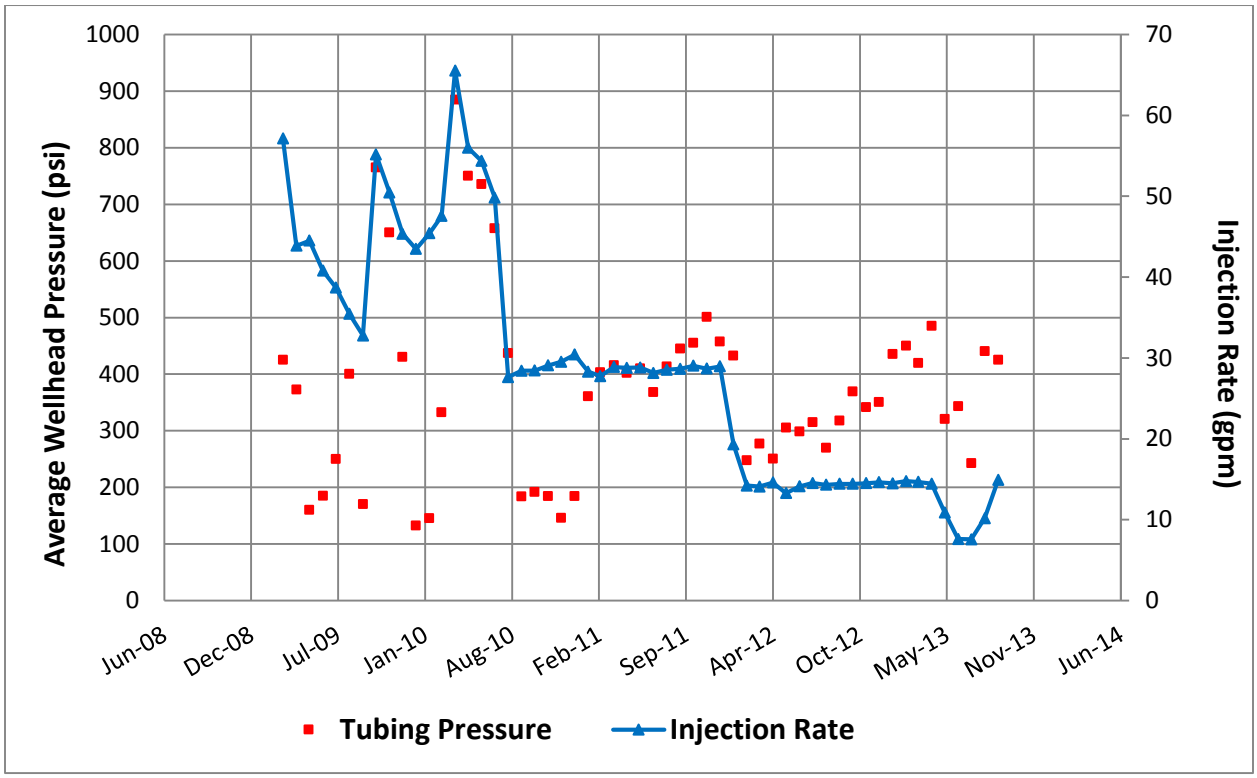


FIGURE G- 7: ELK VALLEY OPERATING BOTTOMHOLE PRESSURE GRADIENT PLOT

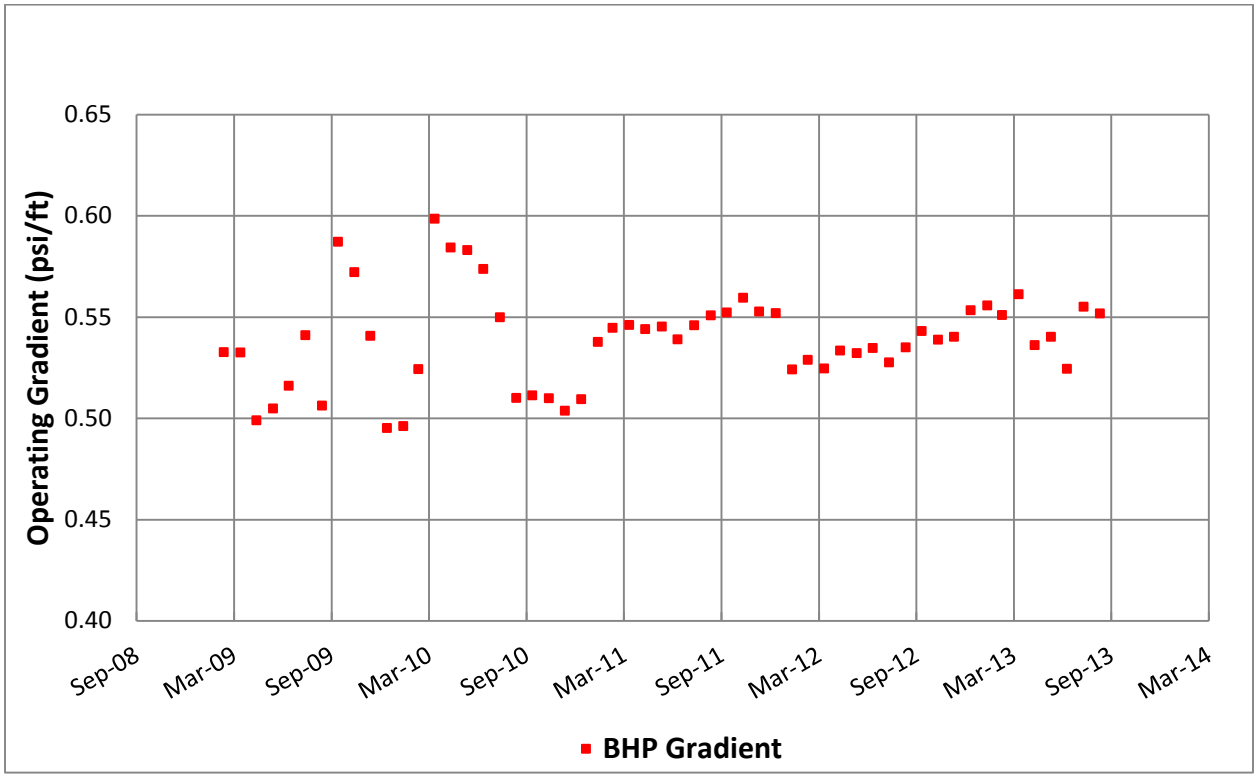


FIGURE G- 8: ELK VALLEY HALL INTEGRAL AND CUMULATIVE EARTHQUAKE EVENTS TANDEM PLOT

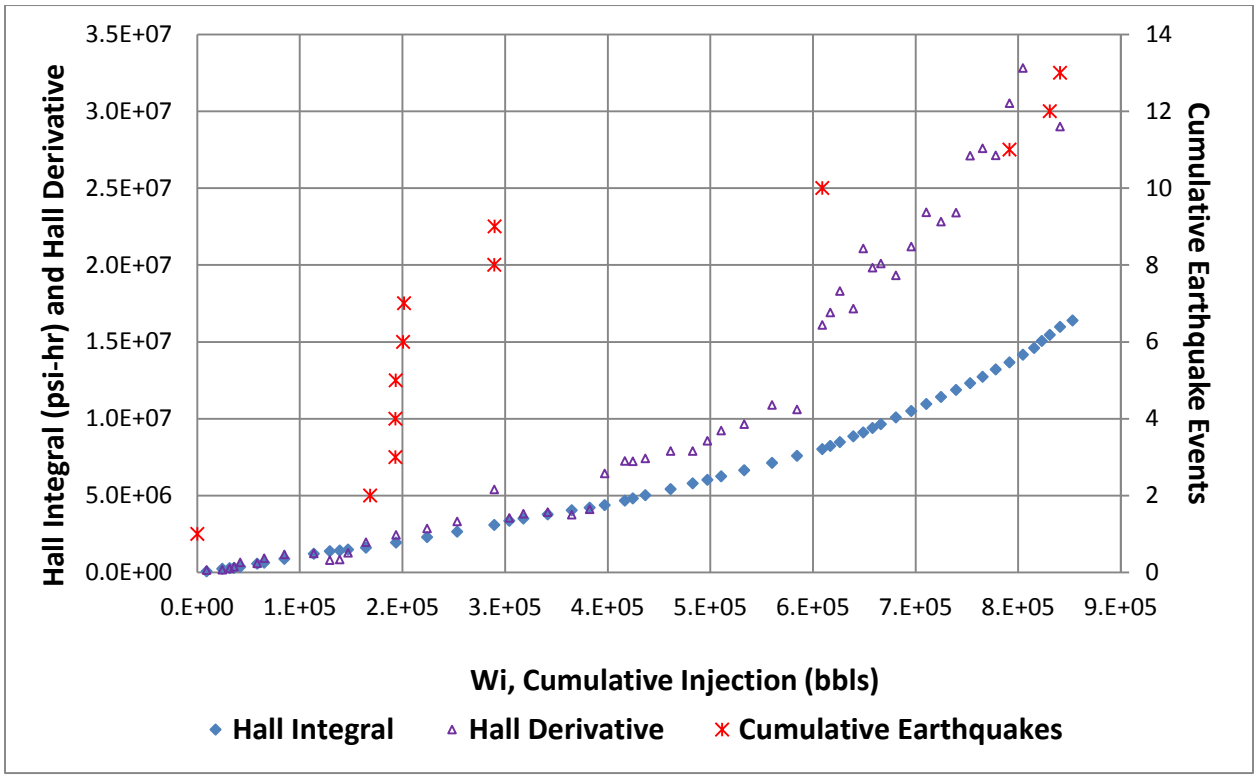


FIGURE G- 9: EXPANDED ELK VALLEY HALL INTEGRAL AND CUMULATIVE EARTHQUAKE EVENTS TANDEM PLOT

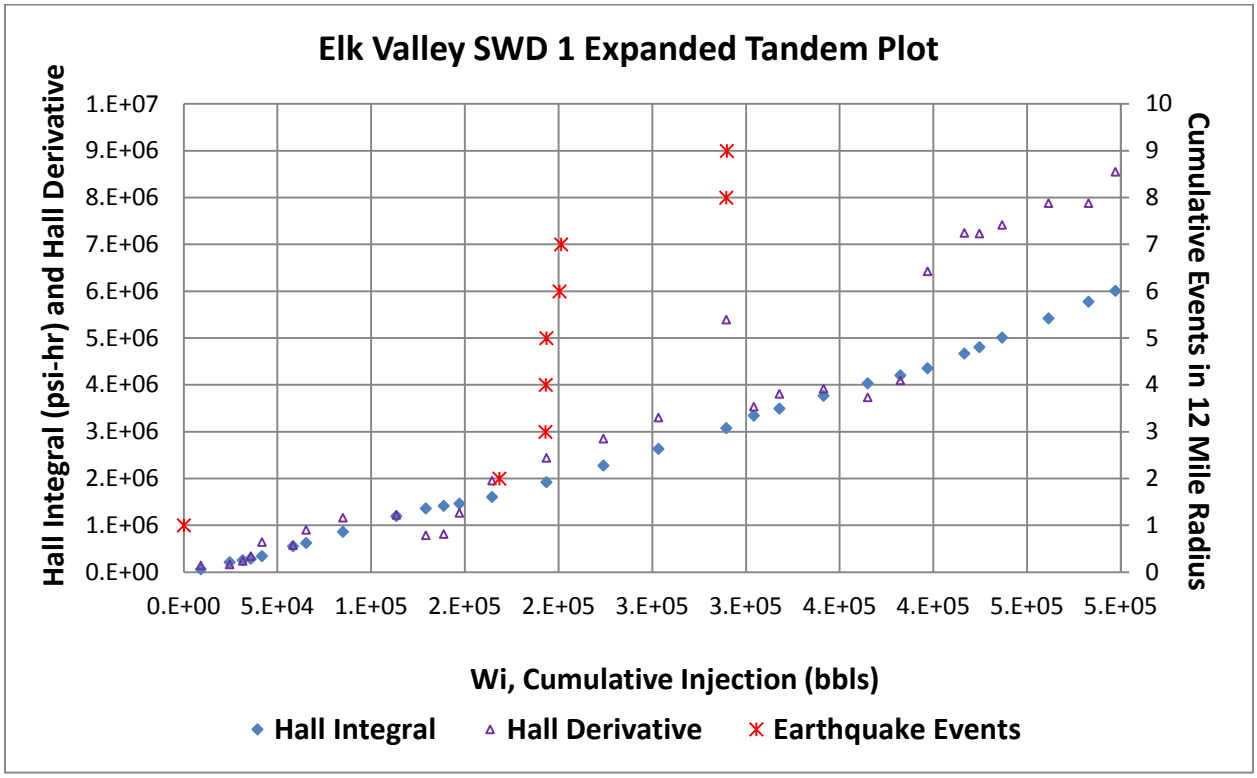
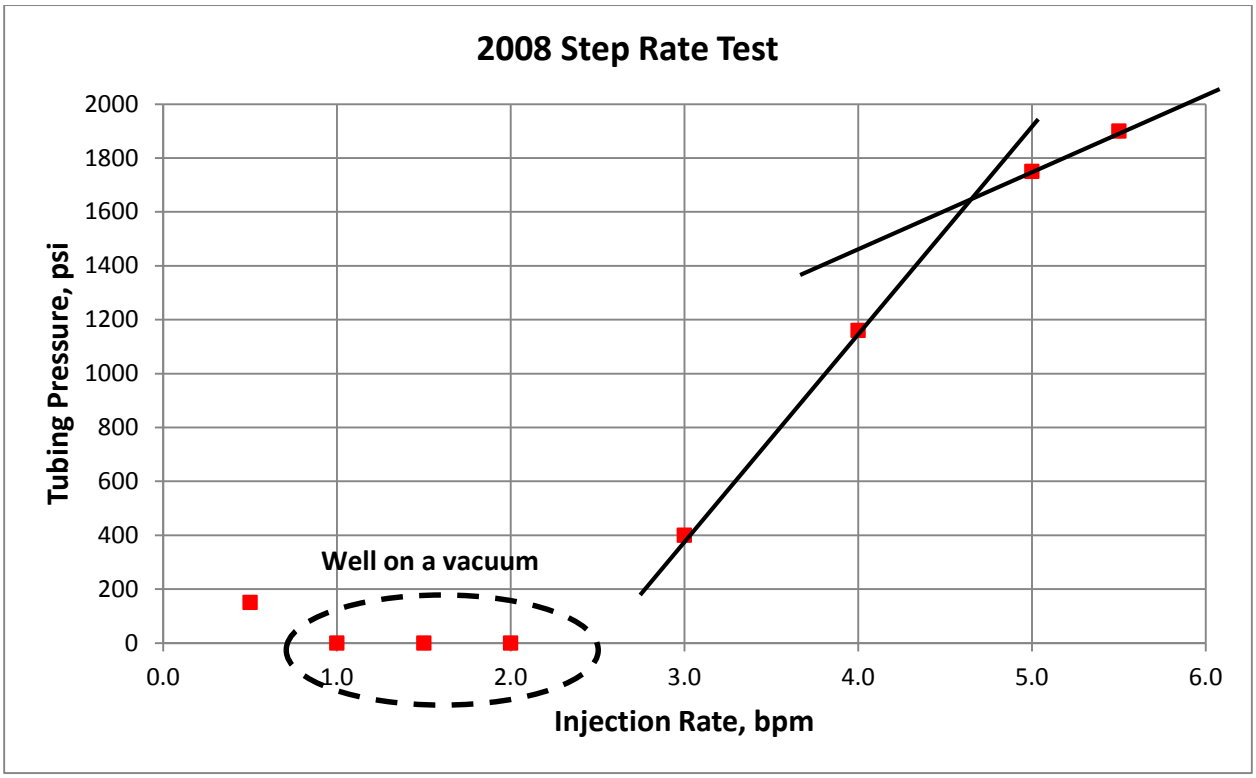


FIGURE G- 10: ELK VALLEY 2008 STEP RATE TEST



APPENDIX H: YOUNGSTOWN, OHIO CASE STUDY

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Table H-1: Northstar 1 Disposal Well Permit Conditions H-4
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All four case studies were considered in the development of the decision model. The state agencies' handling of these events was the basis for some of the approaches listed in the decision model described in APPENDIX B: . Consequently, the Injection-Induced Seismicity Working Group (WG) elected to apply the decision model framework to the case study events. Following the decision model framework, the well in this case study fell under the new well category. Increased earthquake frequency and magnitude following the start of disposal operations raised concern.

YOUNGSTOWN, OHIO CASE STUDY BACKGROUND

Starting on March 17, 2011, a series of 12 small magnitude seismic events occurred in Mahoning County in and around Youngstown, Ohio, culminating in a M4.0 event on December 31, 2011 (Figure H-1). Evidence suggested that a newly permitted Class II saltwater disposal well, the Northstar 1, was the cause of the seismic activity, and the injection well was voluntarily shut down a day before the M4.0 event. The Northstar 1 injection well had been permitted as a deep

stratigraphic test well and was drilled to a depth of 9,184 feet into the Precambrian basement rocks in April of 2010. On July 12, 2010, the Northstar 1 was issued a Class II saltwater disposal permit, and injection operations commenced on December 22, 2010.

To aid understanding area site conditions, the geologic setting, existing oil and gas activity and seismic history are summarized, followed by a focused site assessment that provides details of the disposal well operations.

Geologic Setting

Youngstown is located in Mahoning County near the border of Pennsylvania, on the western flank of the Appalachian Basin. Figure H-2[30], (Baranoski, 2002; ODNR, 2012) illustrates the general structure across Ohio with deep Precambrian structures overlain by Paleozoic beds thickening to the east into the Appalachian Basin. Figure H-3 (ODNR, 2004) shows a regional stratigraphic column. The Utica and Marcellus shale plays are thin in eastern Ohio, thickening into the Appalachian basin to the east (Figure H-4).

Very little well control is available for the basement Precambrian structure, but regional maps based on well control combined with seismic lines have been compiled (Baranoski, 2002, 2013; Pennsylvania Geological Survey, 2005). The 2013 Baranoski publication includes maps of all the Precambrian wells drilled since 2002. The Baranoski Precambrian maps do not show faulting in Mahoning County. The regional scale map (Figure H-1) shows the closest known fault to be about 20 miles away.

Oil and Gas Activity

Shallow oil and gas activity is plentiful in the area, with production from the upper Devonian Berea and lower Silurian sandstones. The first Class II saltwater disposal well was permitted in Mahoning County in 1985, and eight more wells were converted to Class II injection between 1985 and 2004. These Class II injection wells utilized depleted oil and gas zones or were plugged backed to shallower, non-oil and non-gas geologic formations for disposal. Injection was predominantly for disposal of production brine associated with conventional oil and gas operations.

With the development of the unconventional shale plays in Pennsylvania and the lack of disposal in Pennsylvania, there was a need for additional disposal operations. To accommodate some of this need, five commercial disposal wells (Northstar 1, 2, 3, 4, and 6) were permitted and drilled in Mahoning County. The permitted disposal zones were the Knox through the Mount Simon

[30] The location is south and west of the view shown in Figure H-1.

Sandstone, but the disposal wells were drilled completely through the Mount Simon and into the Precambrian basement rock.

History of Seismicity

Prior to the March 2011 seismic events, there had been no seismicity epicenters recorded in Mahoning County. However, there is a seismically active zone in western Ohio and several episodically active faults 20 miles (Smith Township fault) and 40 miles (Akron magnetic anomaly) away from Youngstown (Figure H-1) (Baranoski, 2002). The vast majority of all historic and current seismic activity in Ohio occurs within the Precambrian basement rocks.

Seismic monitoring in Ohio was sporadic until establishment of the Ohio Seismic Network (OSN).[31] Prior to 1999, seismic monitoring was sporadic throughout the state, consisting of monitoring at U.S. Geological Survey stations and other smaller monitoring networks. The earlier seismic network distribution made identifying events below a M3.0 difficult. In 1999, the OSN was established with 6 stations, and there were 24 seismic stations in operation in 2011. The seismometer at Youngstown State University was added to the OSN in 2003.

The seismicity search for this case study used a number of databases including USGS Advanced National Seismic System (ANSS), Ohio Seismic Network (OSN), Eastern, Central & Mountain States NEIC Earthquake database (SRA), Central and Eastern United States CERI Earthquake database (NCEER), Significant U.S. quakes, NEIC Earthquake database (USHIS), Center for Earthquake Research and Information (CERI) and Preliminary Determination Earthquake, NEIC Earthquake database (PDE).

Focused Site Assessment

On March 17, 2011, a series of small magnitude earthquakes began in Mahoning County in and around Youngstown, Ohio (Figure H-1). A nearby commercial Class II disposal well, Northstar 1, was shut in by the Ohio Department of Natural Resources (ODNR) following a M4.3 (M3.9 refined value) magnitude earthquake on December 31, 2011. Based on earthquake activity and the regional seismometer network capabilities, an arbitrary 6 mile (10 km) radius was selected to define the focus area around the well (Figure H-5).

The *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio, Area* published in March 2012 by the ODNR suggests the seismicity was related to Class II disposal activities. The Northstar 1 was drilled 200 feet into the Precambrian

[31] OSN is coordinated by the Ohio Geological Survey of the ODNR

basement rock. The ODNR report also concluded that pressure from disposal activities may have communicated with a fault located in the Precambrian basement rock.

Information Collected

The ODNR standard UIC permit application package submitted prior to October 1, 2012, required some site data, well construction and completion information and other supporting documentation to demonstrate the protection of USDWs.

Data for the five Northstar wells were collected from the ODNR through the Oil and Gas Resources Division website and staff. Permitting documents provided details concerning completion depths, construction information and permit conditions. Supplemental geosciences information was obtained from the deployment of additional seismometers. Operational monitoring reports provided several months of injection rates and wellhead injection pressures, as well as fluid analysis and a step rate test.

Disposal Well in Case Study

Six Northstar disposal wells were permitted for injection near the Youngstown area in 2011. According to the ODNR only one has injected, though only five were drilled and completed open-hole from the Knox into the Precambrian.

Injection activities began in Northstar 1 in December 2010, about 3 months prior to the start of seismic events. A closeup map of the disposal well and earthquake activity in Mahoning County is included in Figure H-5. Two increases in the maximum allowable surface pressure were authorized by ODNR based on the actual specific gravity of the injectate. Permit, construction and completion information for the Northstar 1 disposal well are summarized below:

TABLE H-1: NORTHSTAR 1 DISPOSAL WELL PERMIT CONDITIONS

UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation
3127	yes	2,500	2,000	Top of Knox through 200’ of Precambrian; open-hole completion

TABLE H-2: NORTHSTAR 1 DISPOSAL WELL COMPLETION DATA

Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
8,215’	9,180’	9,184’	5.5” at 8,215’	3.5” at 8,215’

DEPTHS ARE MEASURED DEPTHS IN FEET, NOT TVD

TABLE H-3: NORTHSTAR 1 DISPOSAL WELL OPERATIONS

Initial Disposal	Final Disposal	Plugged and Abandoned
12/22/2010	12/31/11	

ADDITIONAL GEOSCIENCE INFORMATION

The Cambrian Knox unconformity, which has rarely been penetrated in Mahoning County, marks the top of the disposal zone permitted in the Youngstown area. The ODNR report indicates that the Northstar 1 penetrated the Precambrian and encountered primarily biotite, quartz, amphibole and feldspar, with undetermined trace minerals for the first 80 feet before reaching granite. The 2012 ODNR report stated there were indications of high angle fractures around the contact with the granite.

The Ohio Geologic Survey of ODNR collects and maintains information on geology, oil and gas well details, and the OSN data. The permanent seismometer network is tracked by the OSN.

Due to the continued seismic events occurring in and around the Youngstown area and near the Northstar 1 injection well, four highly sensitive, portable seismic units on loan from Lamont-Doherty Earth Observatory were deployed on December 1, 2011 (Tomastik, 2013; Kim et al., 2012). A later publication (Kim, 2013) relocates epicenters and hypocenters for the 12 earthquakes carried on the OSN website, plus another nine events recorded on the temporary array. Table H-4 summarizes events located within a 6 mile (10 km) radius of the Northstar 1 case study well, as shown in the timeline in Figure H-6. The OSN catalog was used for the first 12 earthquakes in the focus study, and the nine small earthquakes picked up by the temporary network from the Kim publication. The relocated events are designated in Figure H-6 by the plus symbol and are shown in closeup in Figure H-7.

TABLE H-4: YOUNGSTOWN FOCUS AREA SEISMICITY THROUGH SEPTEMBER 30, 2013 (OSN AND KIM, 2013*)

Year	Starting Date	Number of Events	Min.	Avg.	Max.	Ending Date
2011	3/17/2011	11	2.1	2.5	4.0	12/31/2011
2012	1/11/2012	10	0.1	0.6	2.1	2/11/2012
2013	NA	0				NA

*** OSN EVENTS 2011 THROUGH 1/11/2012; TEMPORARY NETWORK 1/12 THROUGH 2/11/2012**

In Kim (2013, Figure 3a), the relocated events define a previously unknown Precambrian basement fault in close proximity to the Northstar 1 well (Figure H-7). This fault was confirmed through evaluation of geophysical logs from the offset deep disposal wells and an interpreted seismic line.

Cross-correlation and wave-form matching were some of the techniques used by Kim (2013) to reanalyze the seismometer readings for the area, resulting in a total of 167 seismic events ($0<M_w<3.9$ between January 2011 through February 2012). Only the 21 events listed above were accurately located seismic events. However, the first of the inaccurately located events occurred 13 days after the Northstar 1 well started injection (Kim, 2013).

Operational Data

Site documentation reviewed included surface maps, location plats, disposal depths and inventory of offset wells within the permit area of review. Well construction details provided to the state included well specifics (casing, cement, perforation and completion information) and disposal conditions (interval, rate and pressure requested). A step rate test was also included with the permit application. In addition, an annual report filed by the operator provided injection volumes and pressure data.

Operational data consisted of quarterly and daily wellhead pressures and injection volumes with hours of well operation included in the daily report data. Surface pressures were converted to approximate bottomhole pressures (BHP) at the tubing seat depth. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the surface pressure and pressure of the hydrostatic column of fluid and subtracting the calculated friction pressure loss. A fluid specific gravity of 1.03 was used in the hydrostatic calculations, based on a fluid lab analysis included in the permit application. An initial static BHP of 3,803 psi was used in the Hall integral calculations based on the initial pressure measured in the inactive offset well Northstar 4.

Petroleum Engineering Review

Data for the Northstar 1 disposal well were divided into two areas: operational data and pressure transient testing, in the form of a step rate test.

Operational Analysis

Three operating data-related plots were prepared including an operational data overview plot (Figure H-8), a monthly operating pressure gradient plot (Figure H-9), and tandem plots of cumulative seismic events and the Hall integral with derivative, based on the calculated average tubing pressures, plotted against cumulative water injection (Figure H-10 and Figure H-11).

The monthly hours reported indicated that the well did not operate continually throughout each month. The Hall integral and derivative functions were prepared as continuous functions from monthly data, and only the hours operated in each month were used in the calculation of the Hall integral and derivative functions. To determine if the earthquake cumulative event trend

followed the Hall integral trend, a tandem plot of both cumulative earthquake events and the Hall integral with derivative response versus cumulative water injection was prepared for the Northstar 1 well, as shown in Figure H-10. Figure H-11 shows an expanded view of the tandem plot responses early in the operational life of the injection well. Observations from each of the plots are provided below.

Overview plot (Figure H-8)

- Higher injection rates followed acid stimulation on August 2, 2011

Operating pressure gradient (Figure H-9)

- Plateau at 0.75 psi/ft bottomhole operating gradient for extended time frame
    - 0.75 psi/ft was basis for determining maximum surface pressure limit in permit

Tandem plot of Hall integral and derivative plot (Figures H-10 and H-11)

- Multiple positive upswings in Hall integral and derivative responses with some corresponding with earthquake events

Pressure Transient Analysis

The June 2010 step rate test conducted to evaluate the injectivity into the well was also reviewed. Test details are provided below.

Step rate test (Figure H-12)

- Designed as an injectivity test to evaluate the formation's ability to accept fluid
- Test conducted through 5.5" production casing
- Pressure fluctuations measured during some of the rate steps
- Full range of pressure gauge (10,000–15,000 psi) excessive for measured pressure range (1,800 psi maximum)
- Unable to determine from the step rate tests report whether the pressure stabilized during each rate step
- Slope breaks on linear plot
    - Several different straight lines could be drawn suggesting breaks after steps 5 and 6
    - Final slope is nearly flat between steps 7 and 8

Summary of Engineering Analysis

The sole Ohio case study disposal well, Northstar 1, had a single step rate test. The test was performed to assess the disposal interval's ability to accept fluid. The quality of the step rate test made it difficult to reliably estimate a fracture gradient; however, the well's maximum surface pressure limit was based on a 0.75 psi/foot BHP operating gradient, as reflected in Figure H-9.

The Northstar tandem plot showed several cycles of increasingly difficult injection followed by periods of enhanced ease of injection. Area seismic events showed some correspondence to the cycles, either occurring during a period of increasingly difficult injection or shortly after a cycle ended, as shown on Figures H-10 and H-11.

Actions Taken by UIC Regulatory Agency in the Youngstown Area

Evidence suggested that Northstar 1, a newly permitted Class II saltwater disposal well was the cause of the seismic activity, and the injection well was voluntarily shut down a day before the M4.0 event. After the M4.0 event on December 31, 2011, the governor of Ohio placed a moratorium on the other three deep injection wells drilled within a 7 mile (11 km) radius of Northstar 1 and put a hold on the issuance of any new Class II saltwater injection well permits until new regulations could be developed.

The ODNR revised its regulations, prohibiting the drilling of Class II injection wells into the Precambrian basement rock, and adopted additional standard permit requirements to facilitate better site assessment and collection of more comprehensive well information. ODNR can require supplemental permit application documentation, such as seismic monitoring or seismic surveys, more geologic data and comprehensive well logs. On a well-by-well basis, ODNR may require a plan of action should seismicity occur, a step rate test, falloff testing and a determination of the initial BHP. A series of operational controls may also be added, such as a continuous pressure monitoring system, an automatic shut-off system and an electronic data recording system for tracking fluids.

In late 2012, ODNR purchased nine portable seismic stations and hired a Ph.D. seismologist to maintain and monitor the seismic network. ODNR is proactively approaching the issue of induced seismicity by conducting seismic monitoring at several new Class II injection well permit locations prior to commencement of injection operations and monitoring seismicity for up to 6 months after initiation of injection. If no seismicity occurs, then these portable units will be moved to the next location.

Youngstown Area Multidisciplinary Integration of Findings

The Northstar injection well was completed into an approximately 900-foot open-hole interval that crossed multiple formations, including faulted basement rock. A production log indicated flow likely occurred into the open-hole interval above the basement rock; however, the entire completion interval was exposed to the well's operating pressure. The well's operating gradient plot plateaued at about a 0.75 psi/foot BHP gradient, which corresponded to the limit used for permitting requirements. The tandem plot displayed, as in the other case studies, several cycles

of decreasing and increasing ease of injectivity with some correspondence between seismic events and a portion of the cycles displaying decreasing injectivity (Hall derivative upswings).

YOUNGSTOWN LESSONS LEARNED

- Initiating dialogue with operators can result in early voluntary action, including well shut-in or acquisition of additional site data.
    - Dialogue between the operator and UIC regulator resulted in the voluntary shut-in of the Northstar 1 disposal well.
    - Acquisition of additional data provided an improved understanding of the area.
    - Increased recording of operational parameters improved the quality of the operational data analysis.
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.
    - Upswings in the Hall integral and derivative plot may indicate a no-flow boundary, such as a fault plane or stratigraphic pinch out, a distance away from the well.
    - Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation, or an increased permeability zone at distance.
- Engaging external geophysical expertise may bring a more accurate location (x,y,z) of the active fault and stress regime through reinterpretation or increased seismic monitoring.
- Lack of historic seismic events may be a function of lack of seismic activity, seismic activity below recordable levels, or epicenters away from population centers.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
    - Deployment of the additional seismometers enabled accurate identification of the location and depths of two major seismic events that occurred on December 24th and December 31st.
- Engage a multidisciplinary combined approach to minimize and manage induced seismicity at a given location.
- Director discretionary authority was used to solve individual site-specific concerns:
    - ODNR acquired additional site information, requested action from operators, and prohibited certain disposal operations.

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APPENDIX H FIGURES

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FIGURE H-1: YOUNGSTOWN OHIO CASE STUDY REGIONAL AREA

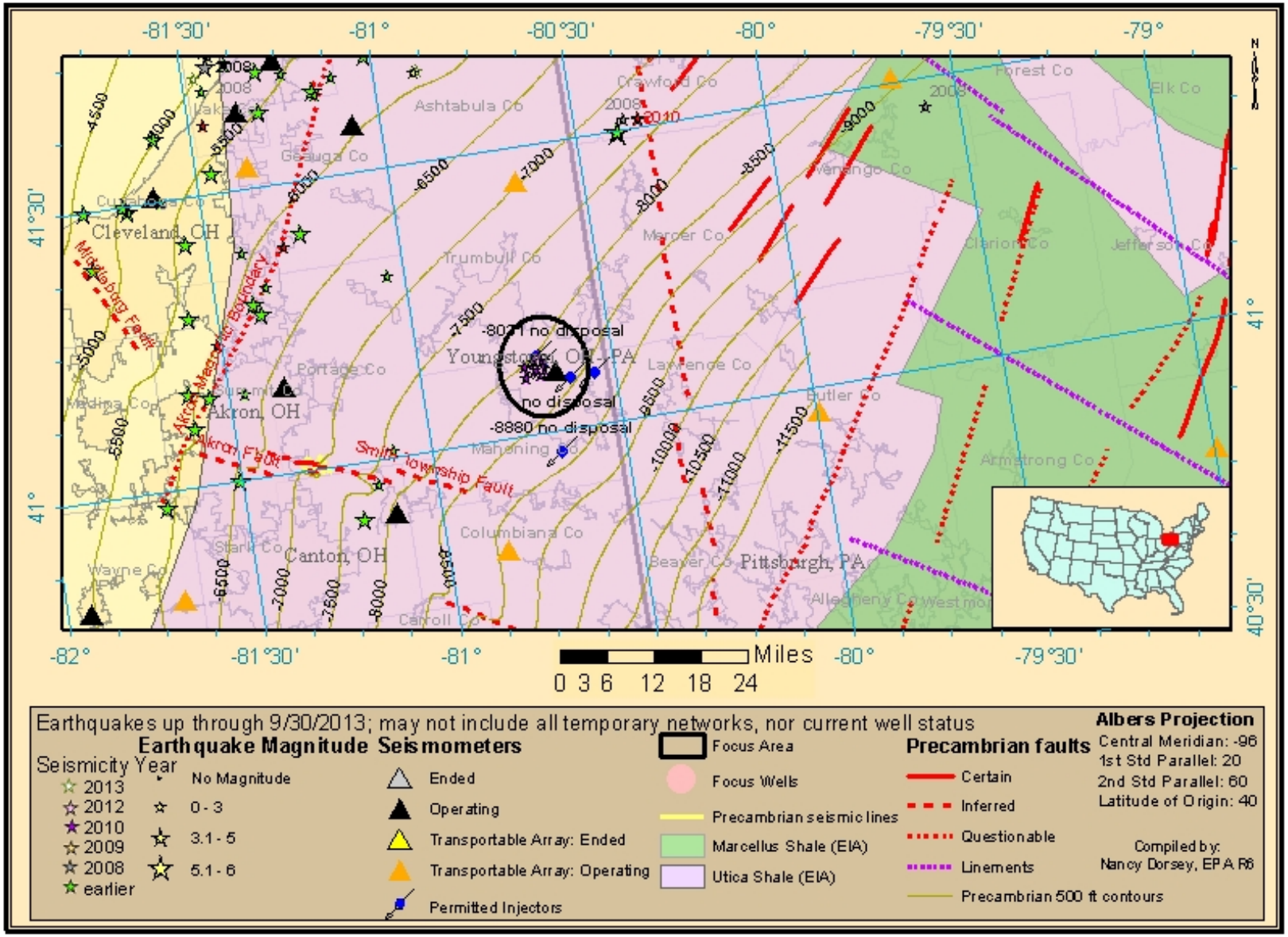
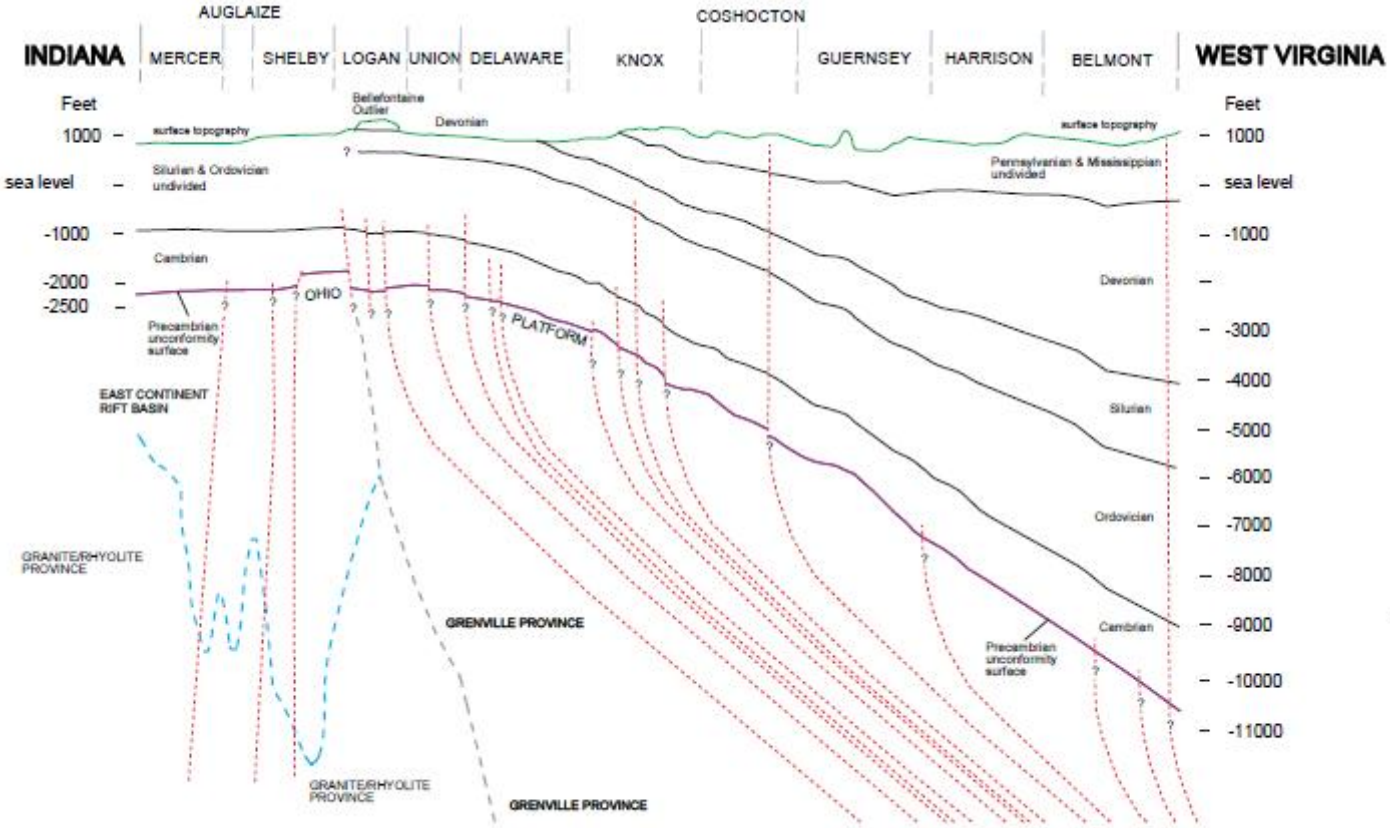


FIGURE H-2: REGIONAL CROSS-SECTION (BARANOSKI, 2002 WITH PERMISSION)



Datum = sea level. Vertical exaggeration = 50X.

Diagram based on interpretation approximately along COCORP OH-1 and OH-2 seismic lines.

FIGURE H 3: GENERALIZES STRATIGRAPHY AND EARTHQUAKE HYPOCENTERS (FIGURE 3B IN KIM, 2013 WITH PERMISSION)

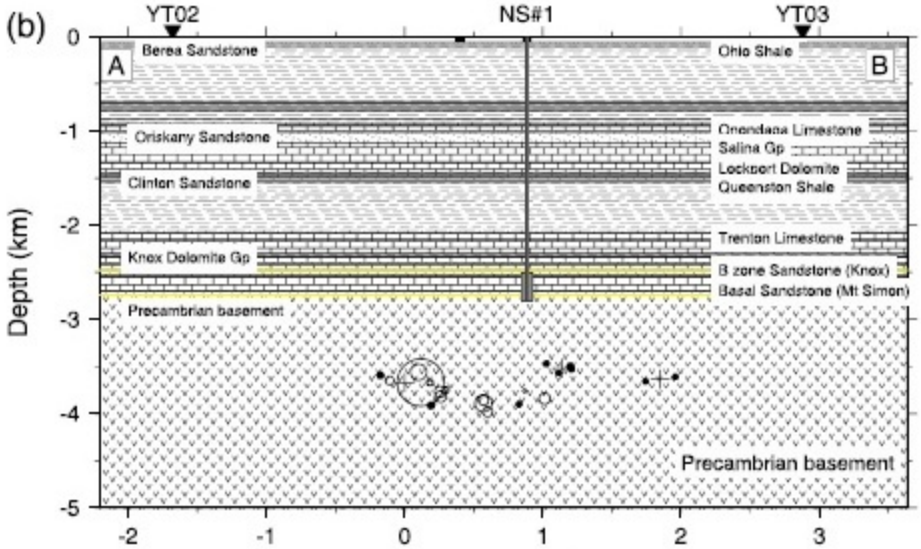


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FIGURE H- 4: UTICA AND MARCELLUS SHALE CROSS-SECTION (FIGURE 5A ON GEOLOGY.COM)

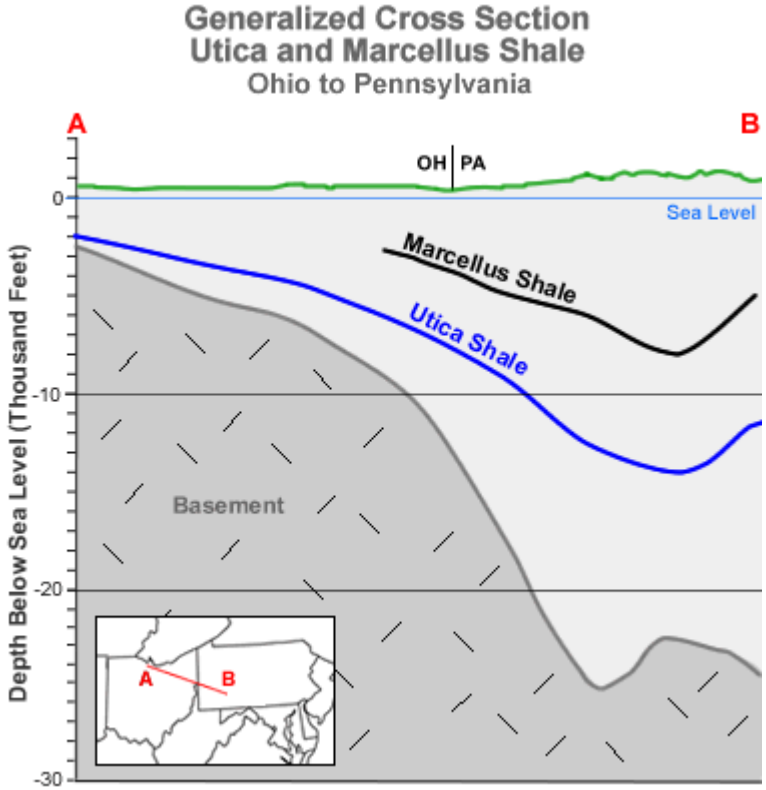


FIGURE H- 5: FOCUS AREA SEISMICTY MAP

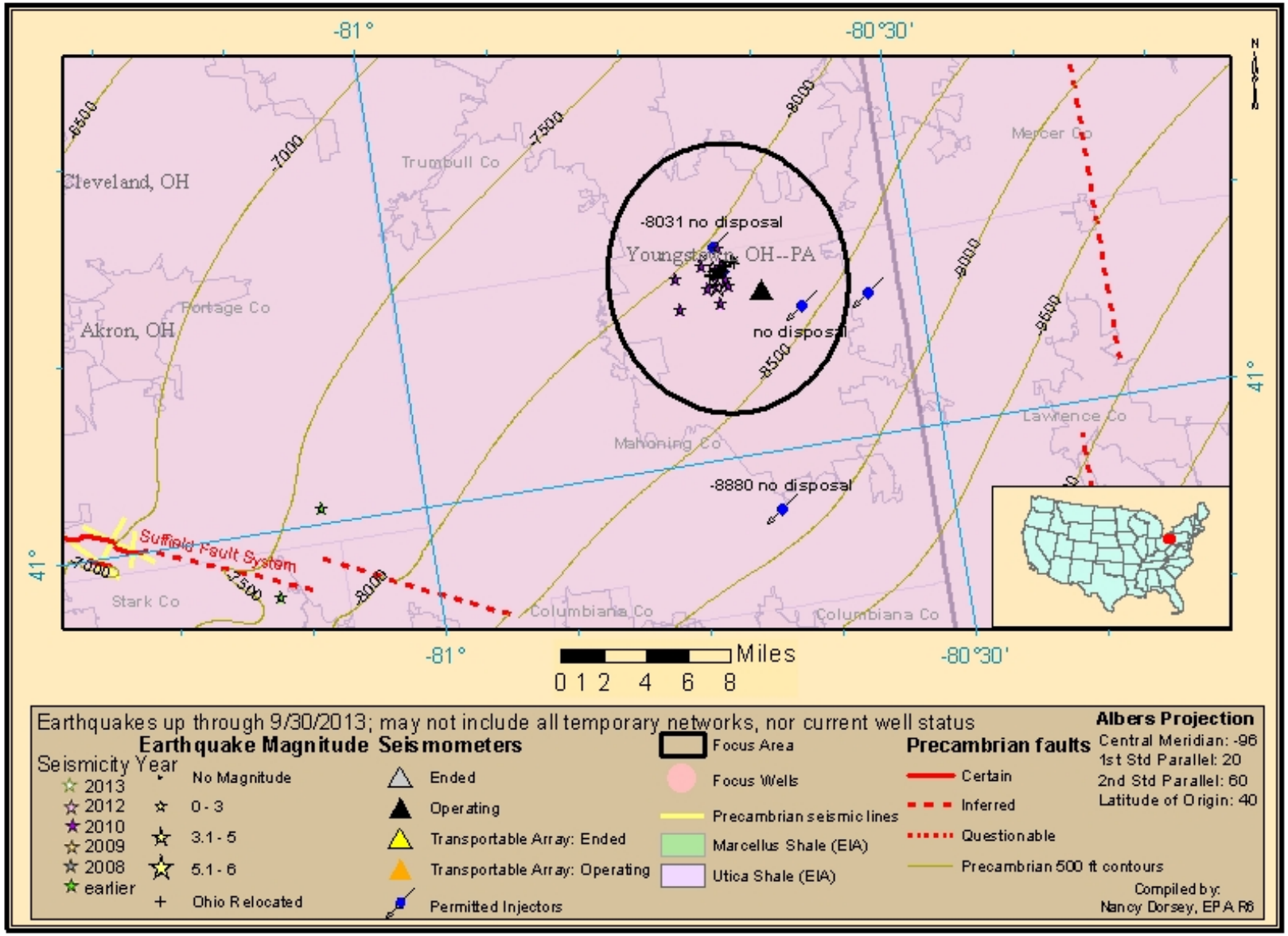


FIGURE H- 6: FOCUS AREA SEISMICITY TIMELINE

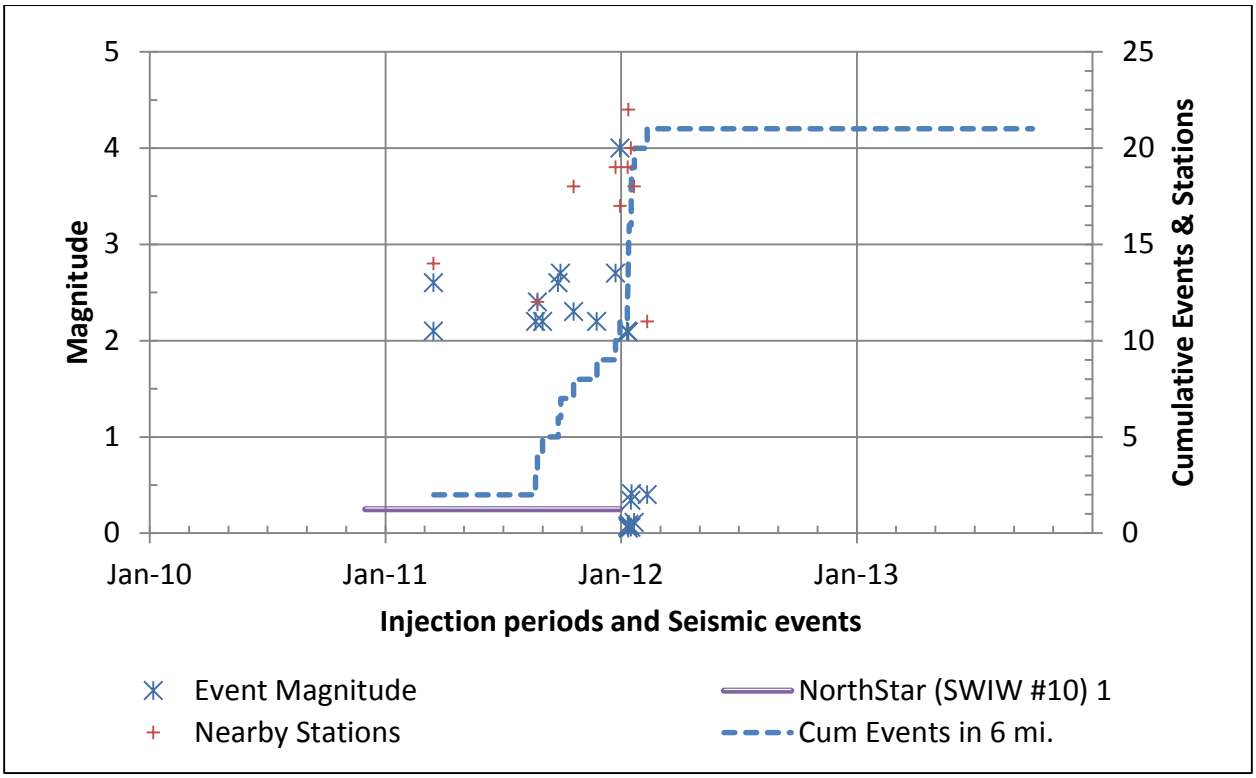
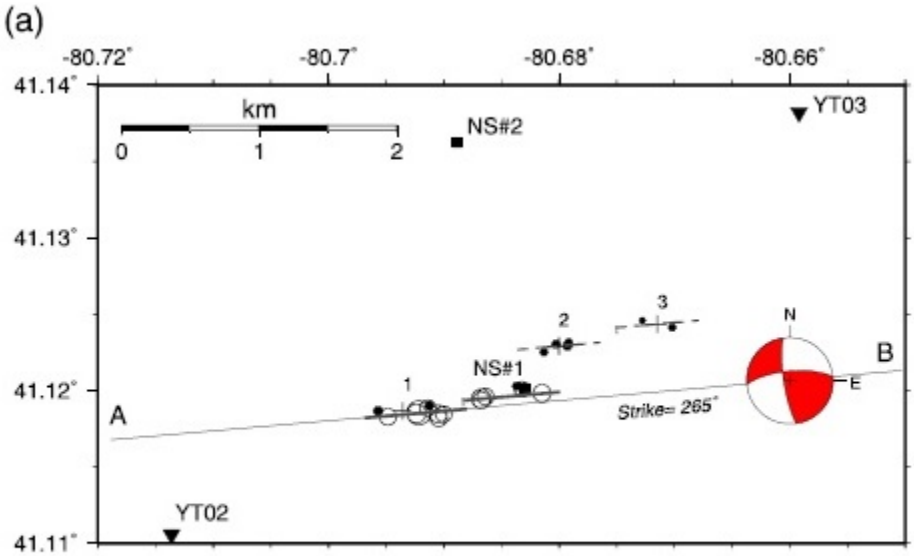


FIGURE H-7: RELOCATED SEISMICITY MAP (FIGURE 3A IN KIM, 2013 WITH PERMISSION)



Kim, W-Y (2013), Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio, *J. Geophys. Res. Solid Earth, 118, Fig 3*

FIGURE H-8: NORTHSTAR 1 OPERATIONAL DATA OVERVIEW PLOT

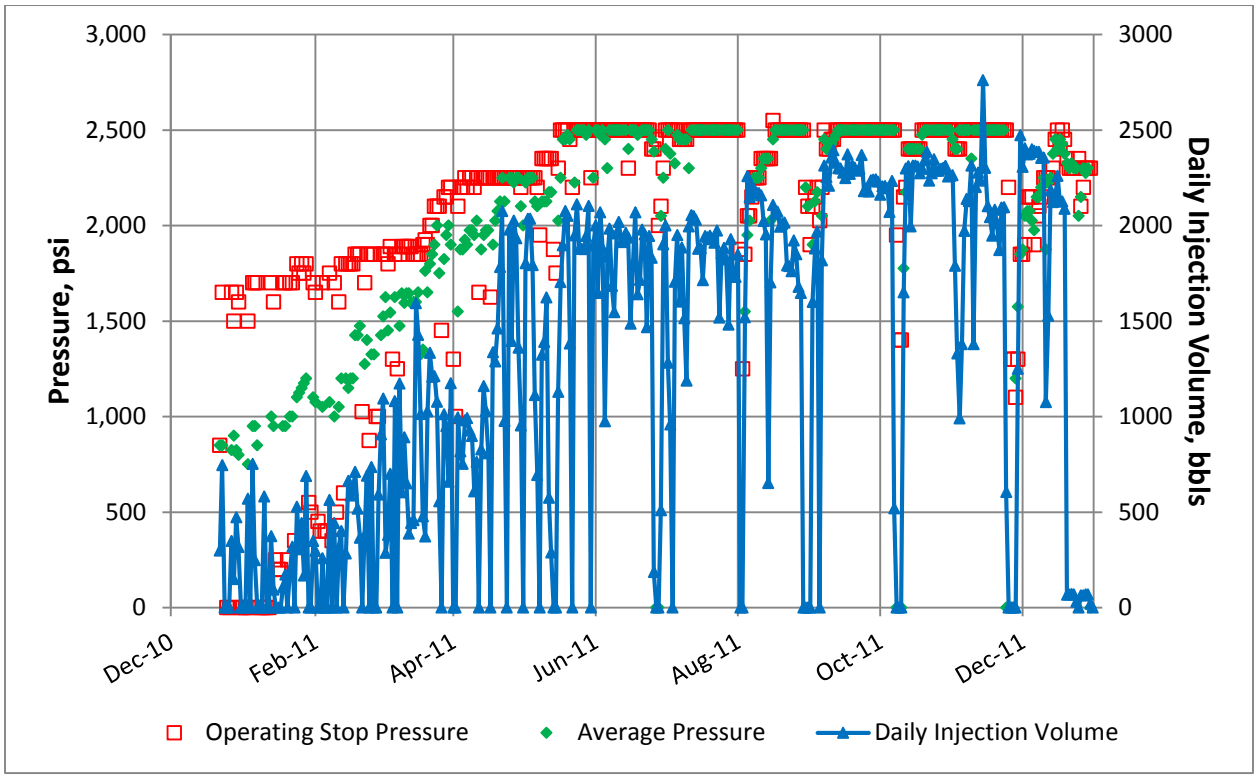


FIGURE H-9: NORTHSTAR 1 OPERATING PRESSURE GRADIENT PLOT

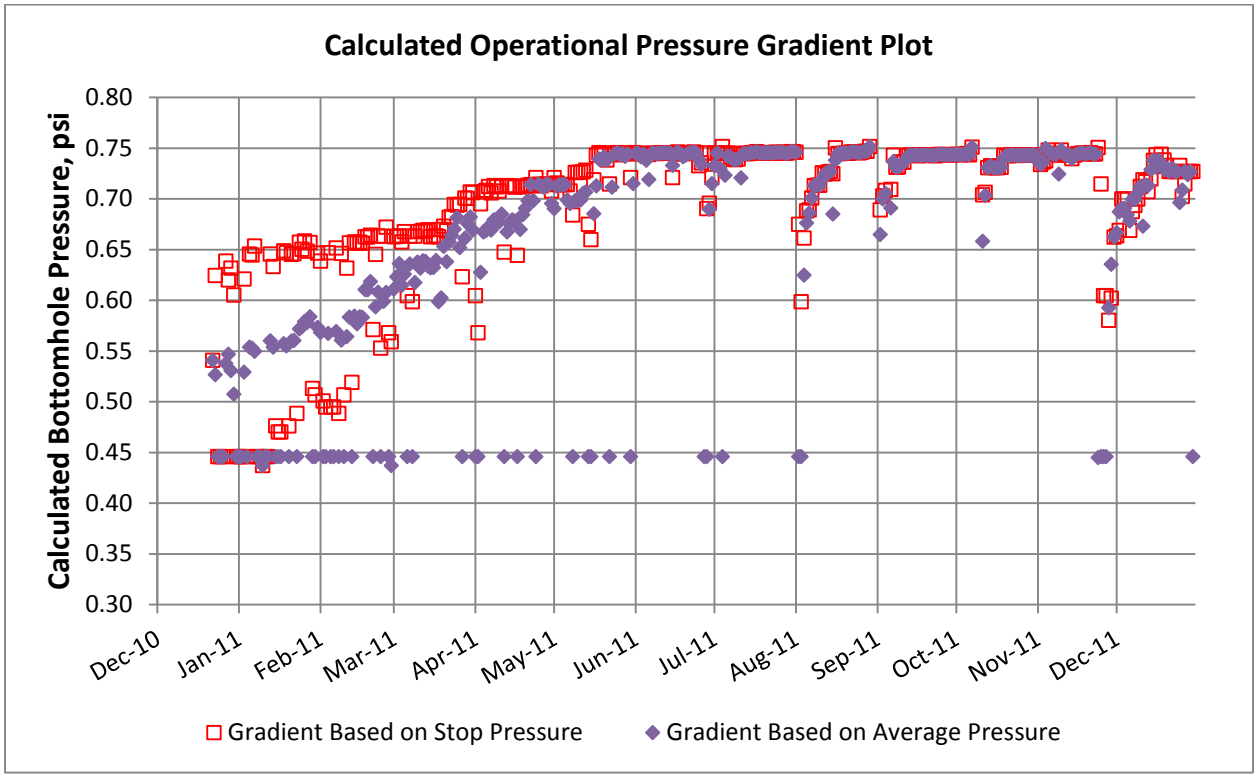


FIGURE H-10: NORTHSTAR 1 TANDEM PLOT OF CUMULATIVE EARTHQUAKES AND HALL INTEGRAL WITH DERIVATIVE

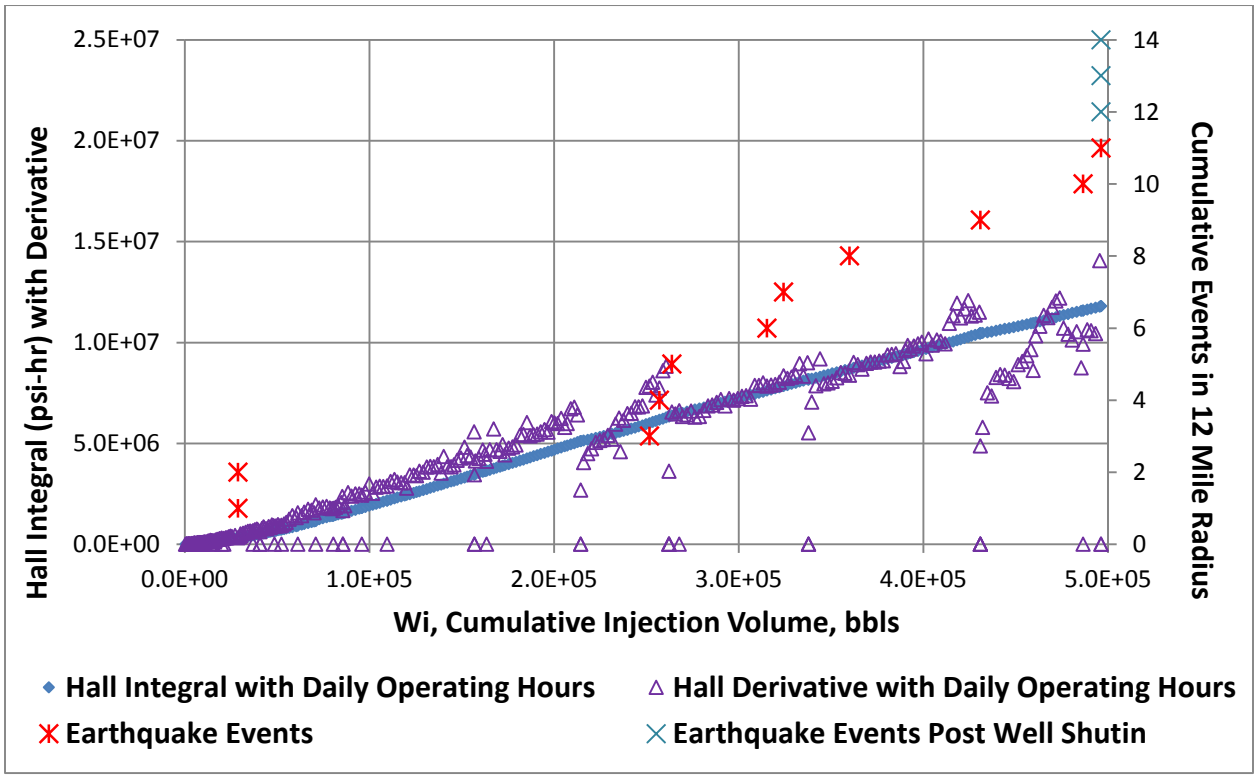


FIGURE H- 11: EXPANDED EARLY TIME TANDEM PLOT

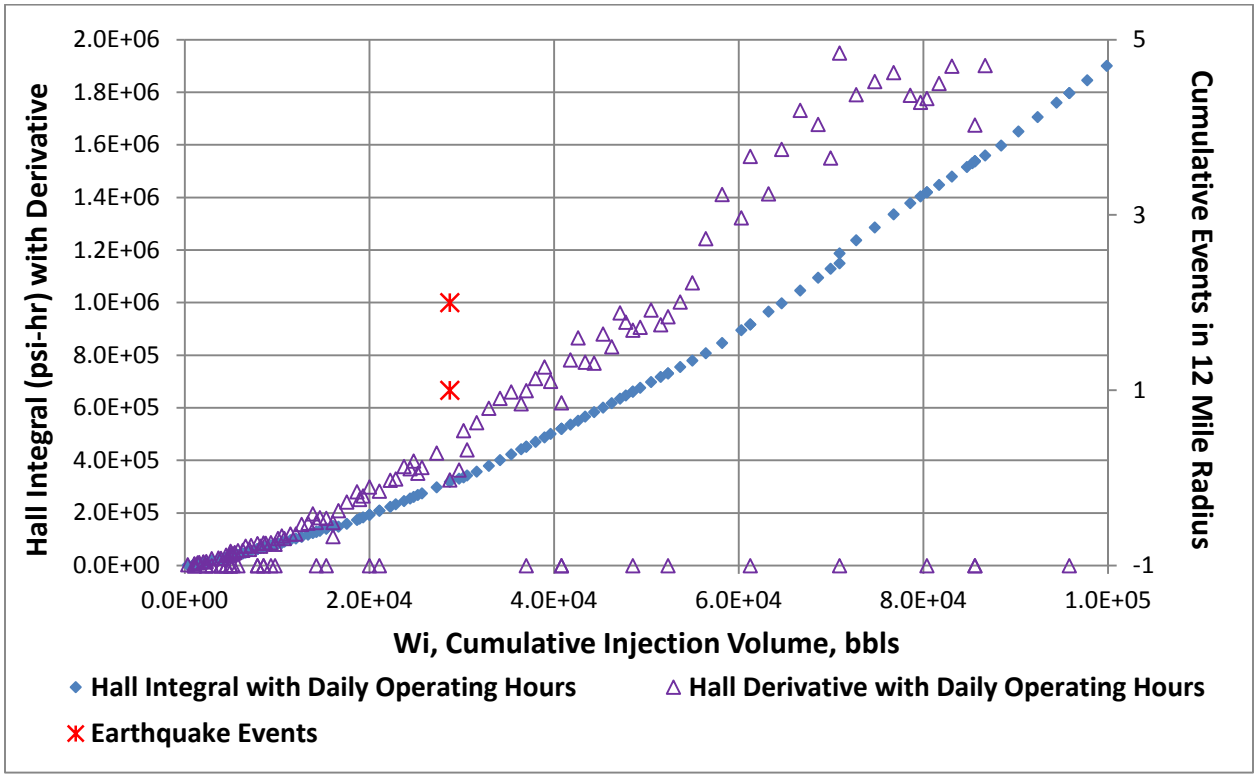
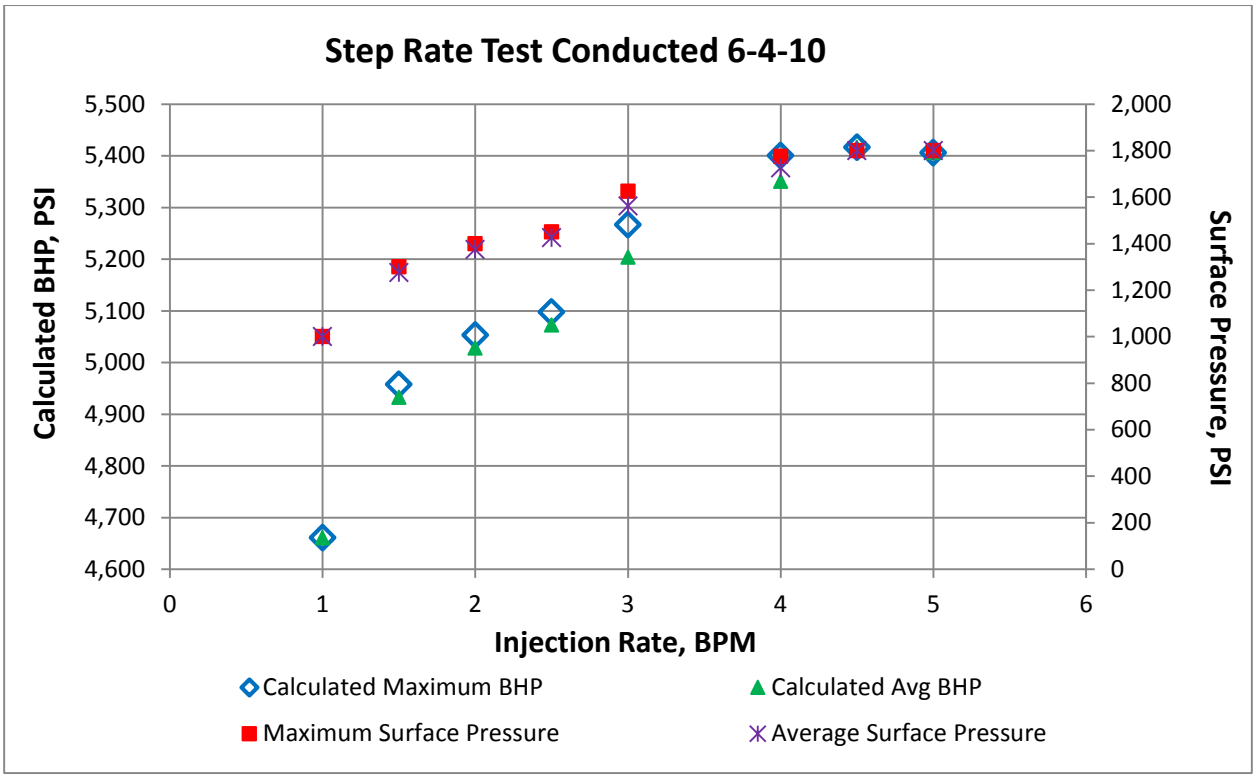


FIGURE H- 12: NORTHSTAR 1 JUNE 4, 2010 STEP RATE TEST



APPENDIX I: ASEISMIC EXAMPLES OF CLASS II DISPOSAL WELL ACTIVITY CAUSING LONG DISTANCE PRESSURE INFLUENCES

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INTRODUCTION

Since pressure buildup is one of the three key components of induced seismicity associated with Class II disposal wells, this appendix provides two examples of pressure buildup that extended for long distances, though neither example induced seismicity. The examples are included to illustrate abnormal cases of pressure buildup observed from two different Class II disposal well activities. The examples illustrate that reservoir pressure distribution from disposal activities is site-specific and dependent on geology and reservoir characteristics. The first example illustrates pressure movement through a linear trend, and the second illustrates the cumulative pressure effect from multiple Class II wells completed in the same formation. These two examples also demonstrate the benefits of reservoir pressure measurements and the applicability and usefulness of pressure transient testing techniques.

The area of review determination for Class II disposal wells covered by the federal Underground Injection Control (UIC) regulations includes calculation of the pressure buildup using radial flow equations or, alternatively, use of a fixed ¼ mile (0.402 km) radius from the disposal well (40 CFR §146.6). However, reservoir quality or reservoir flow characteristics may extend pressure influence from the disposal activity beyond a ¼ mile radius from the well. Further, if the reservoir pressure does not dissipate radially from the disposal well, the radial flow equations in the regulations may not be applicable for calculating the zone of endangering pressure influence. Reservoir pressure buildup is also additive, so offset wells completed in the same disposal zone may need to be considered. The Director can use discretionary authority to assess the area of review for special site-specific circumstances.

Example of Extended Directional Pressure Trend

Background

Three inactive wells, two located approximately 1 mile (1.6 km) from a Class II disposal well (5,115 and 6,006 feet, respectively) and one just over ¼ mile (1,584 feet) (1559 m, 1830 m, and 482 m respectively) from the disposal well experienced an increase in surface pressure. These three wells were located in an east-northeast directional trend from the disposal well. The disposal well was the only well operating at a pressure exceeding the highest surface pressure measured at one of the inactive wells. The disposal well started injection approximately 5 months prior to the discovery of the increased pressure in the three abandoned wells. Other inactive wells located closer to the disposal well showed no pressure increase.

After identification of the well of concern, an interference testing procedure (see below) was designed to evaluate whether the disposal well was hydraulically communicating with the inactive wells. The test was designed to establish repeatability of pressure responses if communication was present. The test also required monitoring fluid levels in additional wells located outside the suspected directional trend for possible pressure responses. A falloff test concluded the testing of the disposal well.

Interference Test Summary

As illustrated in Figure I-1, the interference test consisted of a background period, a 1-week stabilization period with the disposal well shut in, 1 week with injection, and a 1-week falloff (shut-in) period in the disposal well. During the injection period, the operator maintained as constant an injection rate as possible. No other active injection was present in the test area. During the background period, digital recording surface pressure gauges were installed on the disposal well and the three inactive wells experiencing surface pressures to monitor pressure responses during the test. The disposal well operator also installed an inline flowmeter on the disposal well. In addition to surface pressure readings, fluid level measurements were collected at the other well locations.

Measured Offset Well Pressure Responses

As shown in Figure I-2, the pressure response between the disposal well and three wells monitored with digital surface pressure gauges indicated direct communication. The repeatability of the pressure response was observed in all three wells. The lag time for the pressure response at each monitored well (Figure I-3) was much shorter than anticipated, and atypical of a radially homogeneous reservoir. The response times were not significantly different between the well located 1,584 feet from the disposal well and the two wells located 5,115 and 6,006 feet away. The magnitude of the pressure response varied, but a pressure response was

still observed. The fluid levels monitored in other area wells plotted in Figure I-4 did not suggest any communication with the disposal well.

Analysis of Disposal Well Pressure Data

The disposal well pressure transient test data measurements, when reviewed and analyzed, indicated a strong linear flow signature. Pressure transient analysis provided an approach for identifying non-homogeneous, non-radial flow reservoir behavior at the disposal well. The elevated pressures from the disposal well exceeded the ¼ mile (402 m) radius area of review allowed for Class II underground injection control permits. The reservoir's linear flow behavior could not be explained based on a review of available geologic and reservoir information. The disposal well was shut in and later plugged and abandoned.

The disposal well pressure responses were plotted on a log-log plot as a diagnostic tool for identifying the flow regime signature away from the well. The log-log plots of the disposal well pressure response during the stabilization and falloff periods suggested bilinear (¼ slope) and linear (½ slope) reservoir flow characteristics (see Figures I-5 and I-6, respectively). A bilinear (¼ slope) trend was observed for the entire test period during the stabilization whereas the falloff test period exhibited bilinear flow (¼ slope) followed by a linear flow characteristic (½ slope).

Type curve matches were completed, using PanSystem® pressure transient software, on the disposal well pressure response during the stabilization and falloff periods. A single fracture model type curve match estimated a very low reservoir permeability and an unrealistically long fracture half-length, nearly a mile (1.6 km) in length for both periods (see Figures I-7 and I-8). This fracture half-length suggested the well was in communication with a linear fault system.

Monitoring Well Interference Tests

The pressure interference response recorded at the three inactive wells with surface transducers was also analyzed. The measured pressure response at all three wells located 1,584, 5,115, and 6,006 feet in an east-northeast trend line from the disposal well was an easily measureable level with minimal lag time after a rate change at the disposal well. The repeatability of the results confirmed communication with the disposal well. The pressure transient test analyses of the interference data were marginal. The interference pressure responses measured at the three wells all demonstrated behavior outside the range of the exponential integral (Ei) type curve typically used for radial flow analysis, but did highlight the non-homogeneous nature of the disposal formation.

During the disposal well falloff period, the associated early time pressure response on the log-log plot for the well located 1,584 feet east-northeast of the disposal well (see Figure I-9) exhibited a more rapid response than the typical Ei type curve, suggesting a naturally fractured reservoir

characteristic or indication of directional permeability. The middle portion of the test, which matched to the Ei type curve, resulted in an unrealistically high estimate (21 darcies) of reservoir permeability before deviating off the type curve.

During the disposal well injection period, the pressure response from the well located 5,115 feet east-northeast displayed two different Ei type curve responses on the log-log plot (see Figures I-10 and I-11). The Ei type curve results from the early portion of the test also estimated an unrealistically high (141 darcies) reservoir permeability, but a much lower permeability (28 md) was estimated from the Ei type curve match of the later portion of the test.

During the stabilization period, the pressure response for the well located 6,006 feet from the disposal well also illustrated atypical pressure responses on the log-log plot (See Figure I-12). No match was attempted of the scattered early data. A type curve match in the middle portion of the test resulted in a permeability estimate of 488 md. The late time pressure response deviated off the Ei type curve.

The repeatable pressure response in the three abandoned wells confirmed that a linear pathway from the disposal well was present. Pressure transient testing at the disposal well also confirmed the presence of a linear flow environment. The interference test analyses also demonstrated a non-homogeneous reservoir. This example illustrates a long distance directional pressure influence through a linear pathway.

Example of Cumulative Pressure Effect from Multiple Class II Wells

This second example covers a facility with a many years of bottomhole pressure (BHP) records experiencing a sudden substantial increase in static reservoir pressure, with no corresponding increase in injection rate.

Background

Disposal well operations with regular BHP monitoring began in 1981. Disposal volumes at the pressure-monitored disposal well (henceforth the monitored well) facility remained relatively constant until 2006, when reservoir pressure began increasing substantially (See Figure I-13). The disposal interval ranges from 15–50 feet in thickness, with an average permeability of 70 md and 13 percent porosity. No cause for the approximately 500 psi pressure increase was identified within 2 miles (3 km) of the facility.

Expanded Review Area

A pressure transient analytical analysis was conducted using the above reservoir parameters along with a 35 ft (10 m) net thickness, 0.54 cp viscosity and an injection rate of 100 gpm (3430

BPD). A pressure increase of 31 psi was predicted 15 miles (24 km) away after 10 years of injection. The review area around the monitored well was expanded to 15 miles in an attempt to identify potential sources for the 500 psi reservoir pressure increase. Fourteen Class II disposal wells were identified as likely injecting into the same formation within a 15 mile (24 km) radius of the monitored well (see Figure I-14). Additional Class II disposal wells exist beyond the 15 mile radius but were not included for this demonstration.

Effects of Offset Disposal Activity

Most of the offset disposal activity began in late 2005. One offset well has operated occasionally for an extended period of time, but the majority of the offset disposal activity is more recent. The monitored well is included in the cumulative well count shown on Figure I-15. Figure I-16 illustrates the disposal volumes of the monitored well and cumulative disposal volumes from the other fourteen wells located within the 15 mile (24 km) radius. The cumulative pressure effects of multiple disposal wells completed in the same zone may impact a large area, as illustrated in this example.

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Figure I- 1: Monitored Disposal Well Interference Test Sequence

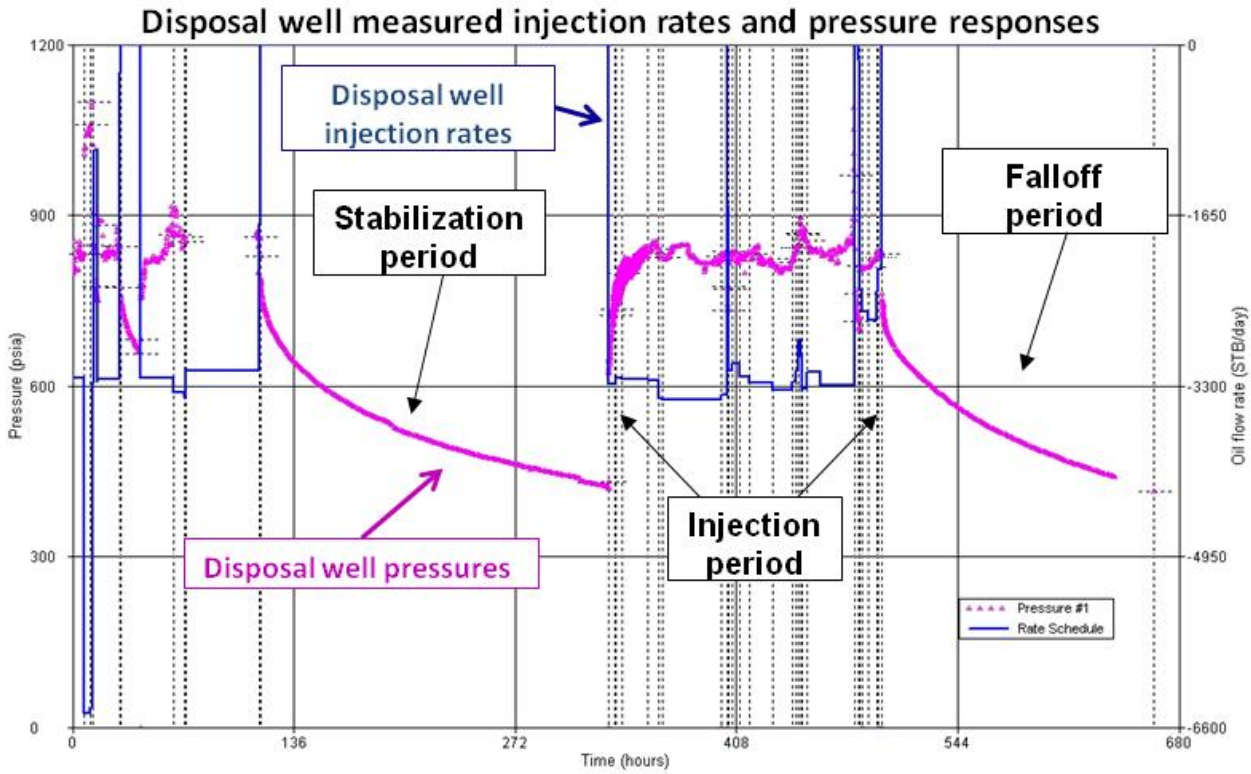


Figure I- 2: Pressure Response at Monitored Disposal Well and Three Offset Wells

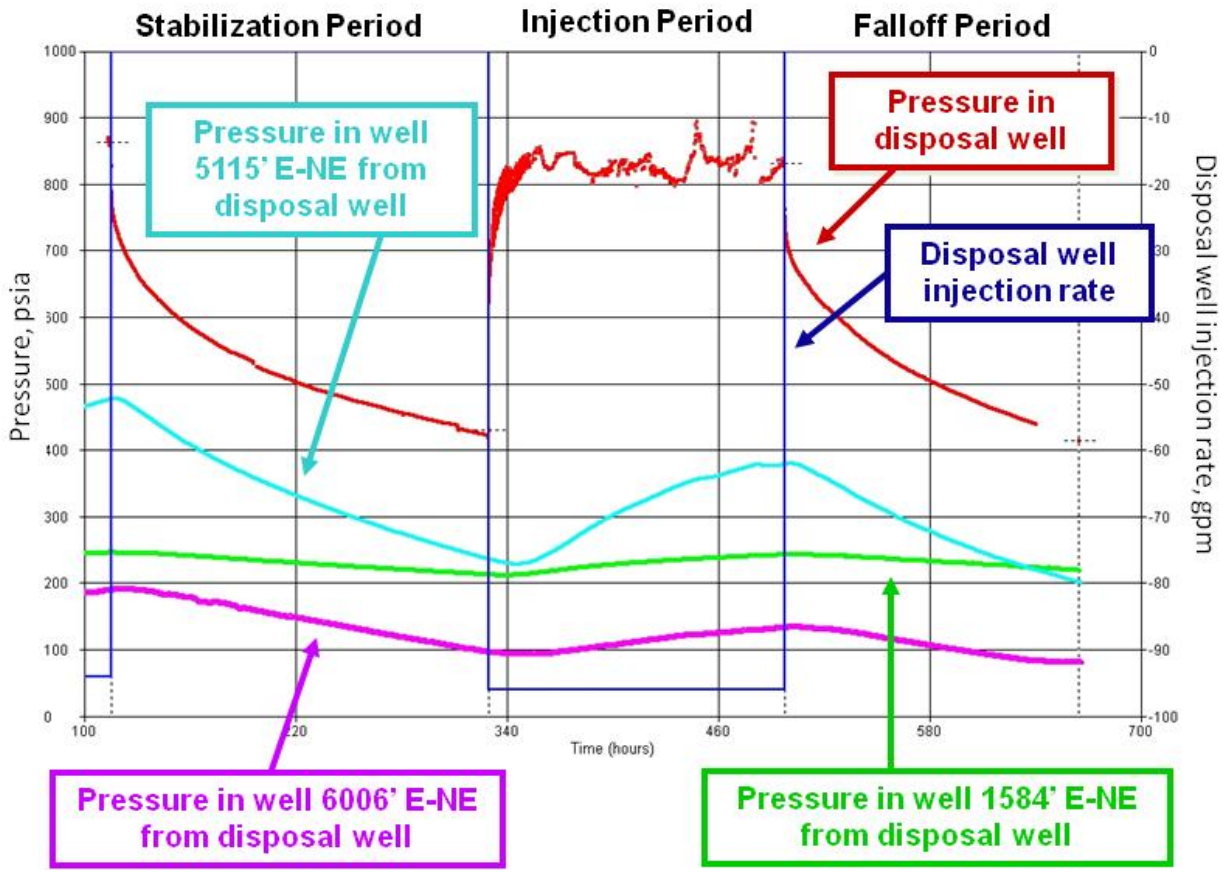


Figure I- 3: Lag Time of Pressure Response at Three Offset Wells

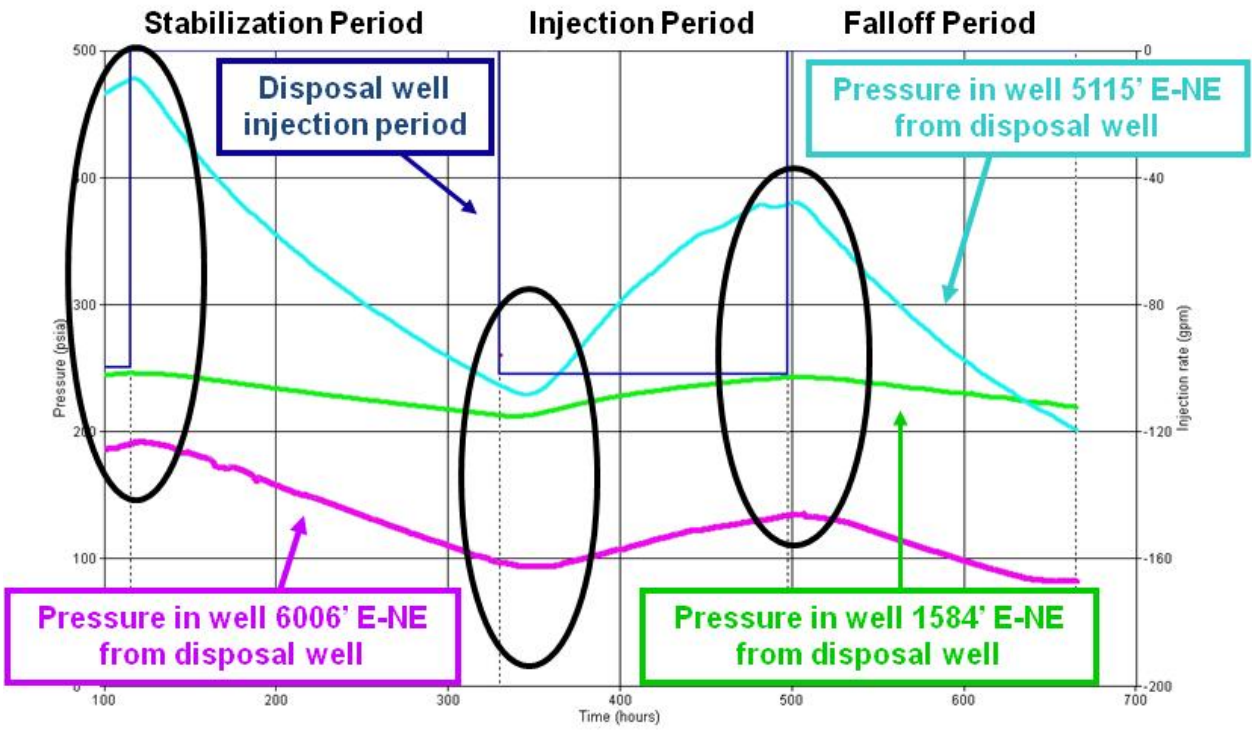


FIGURE I- 4: FLUID LEVEL MEASUREMENTS AT OTHER AREA OFFSET WELLS

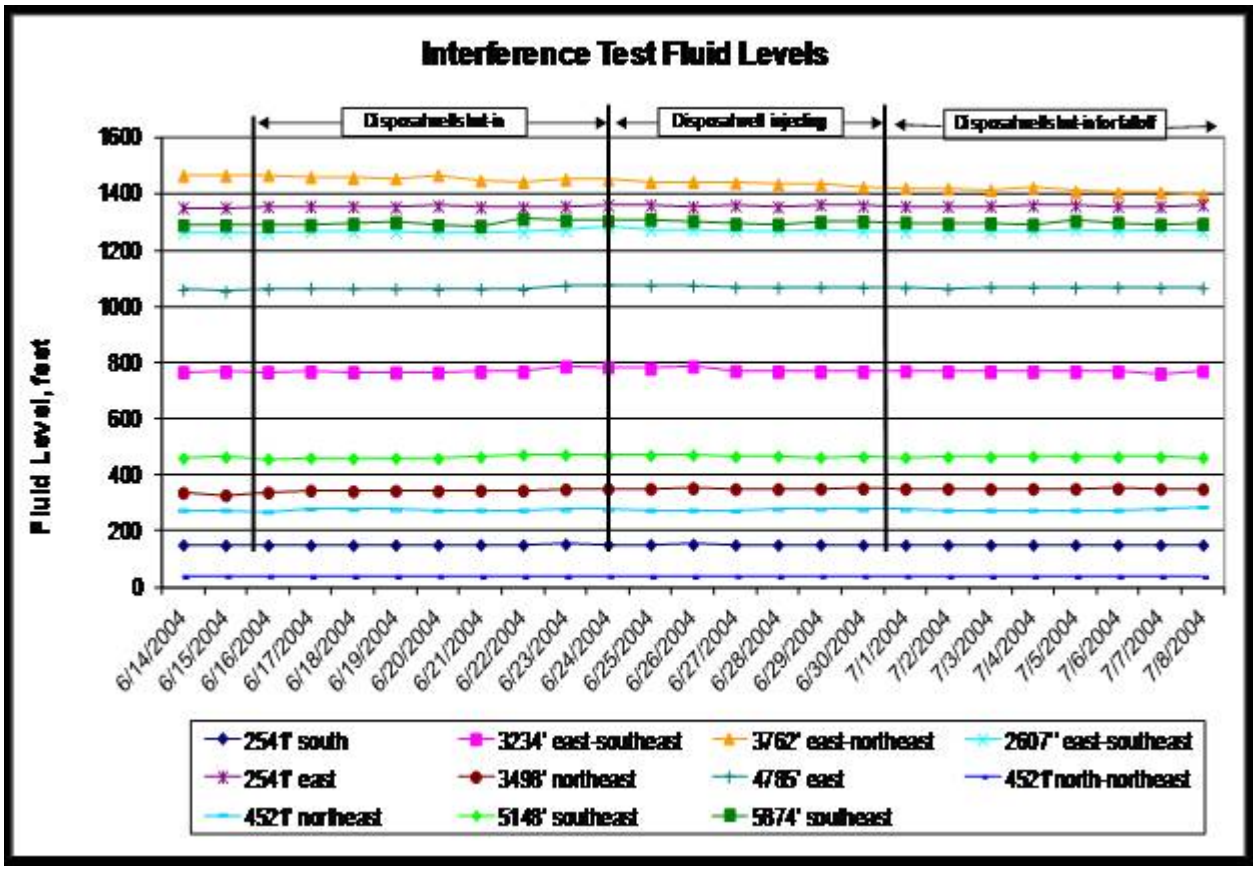


FIGURE I- 5: LOG-LOG PLOT OF MONITORED DISPOSAL WELL PRESSURE RESPONSES DURING STABILIZATION PERIOD

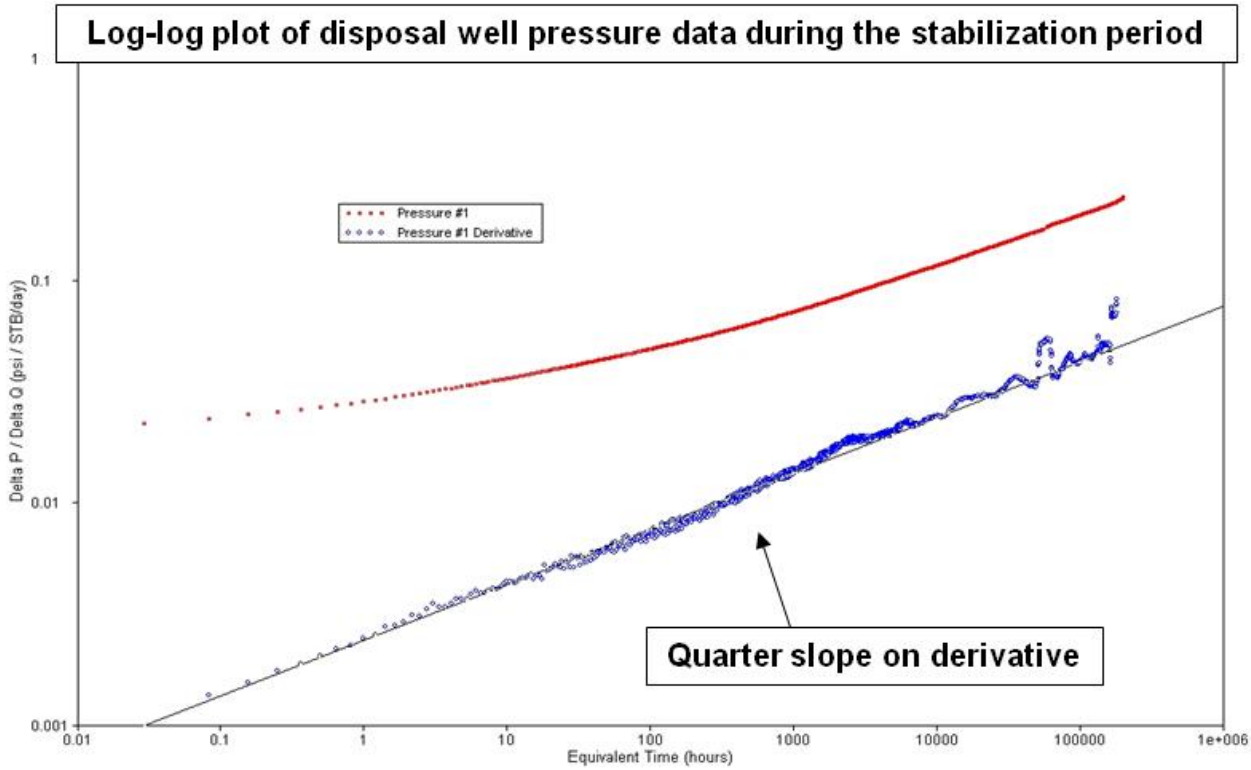


FIGURE I- 6: LOG-LOG PLOT OF MONITORED DISPOSAL WELL PRESSURE RESPONSES DURING FALLOFF PERIOD

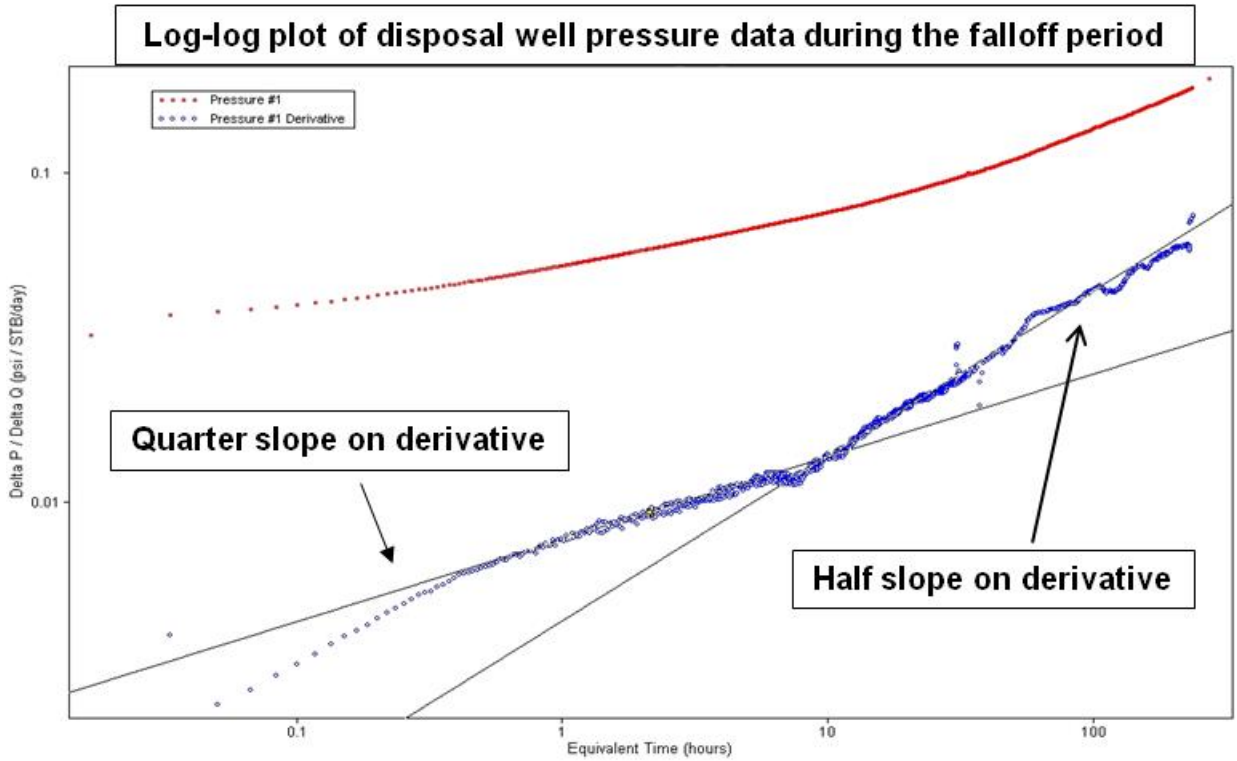


FIGURE I- 7: TYPE CURVE MATCH OF MONITORED DISPOSAL WELL PRESSURE RESPONSES DURING STABILIZATION PERIOD

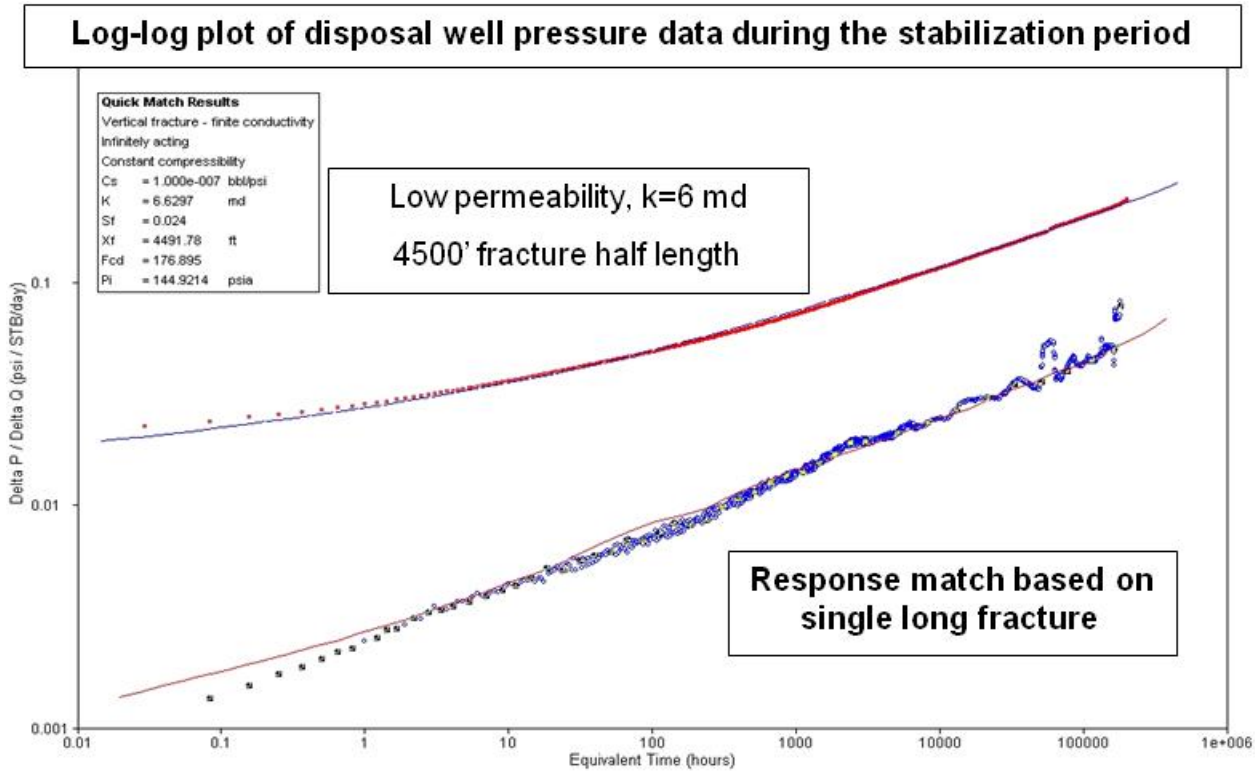


FIGURE I- 8: TYPE CURVE MATCH OF MONITORED DISPOSAL WELL PRESSURE RESPONSES DURING FALLOFF PERIOD

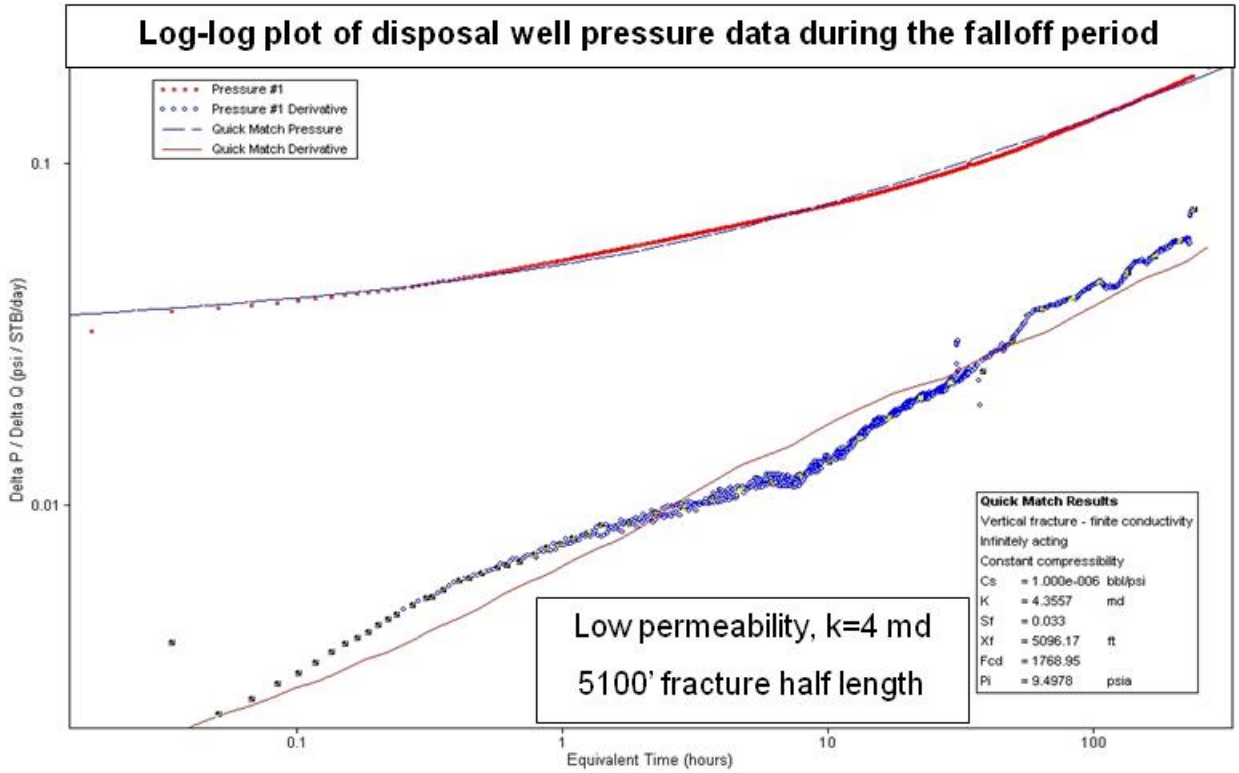


FIGURE I- 9: TYPE CURVE MATCH OF INTERFERENCE TEST PRESSURE RESPONSE AT WELL LOCATED 1584' E-NE

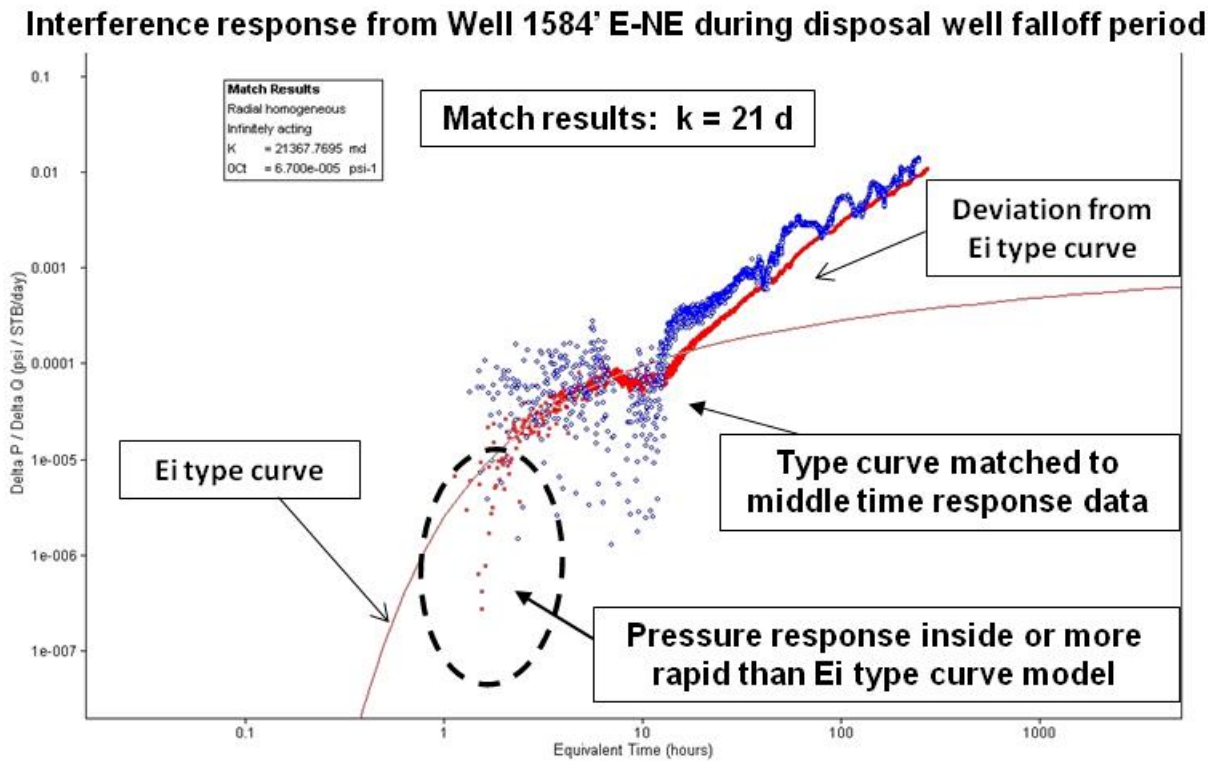


FIGURE I- 10: TYPE CURVE MATCH OF EARLY TIME INTERFERENCE TEST PRESSURE RESPONSE AT WELL LOCATED 5155' E-NE

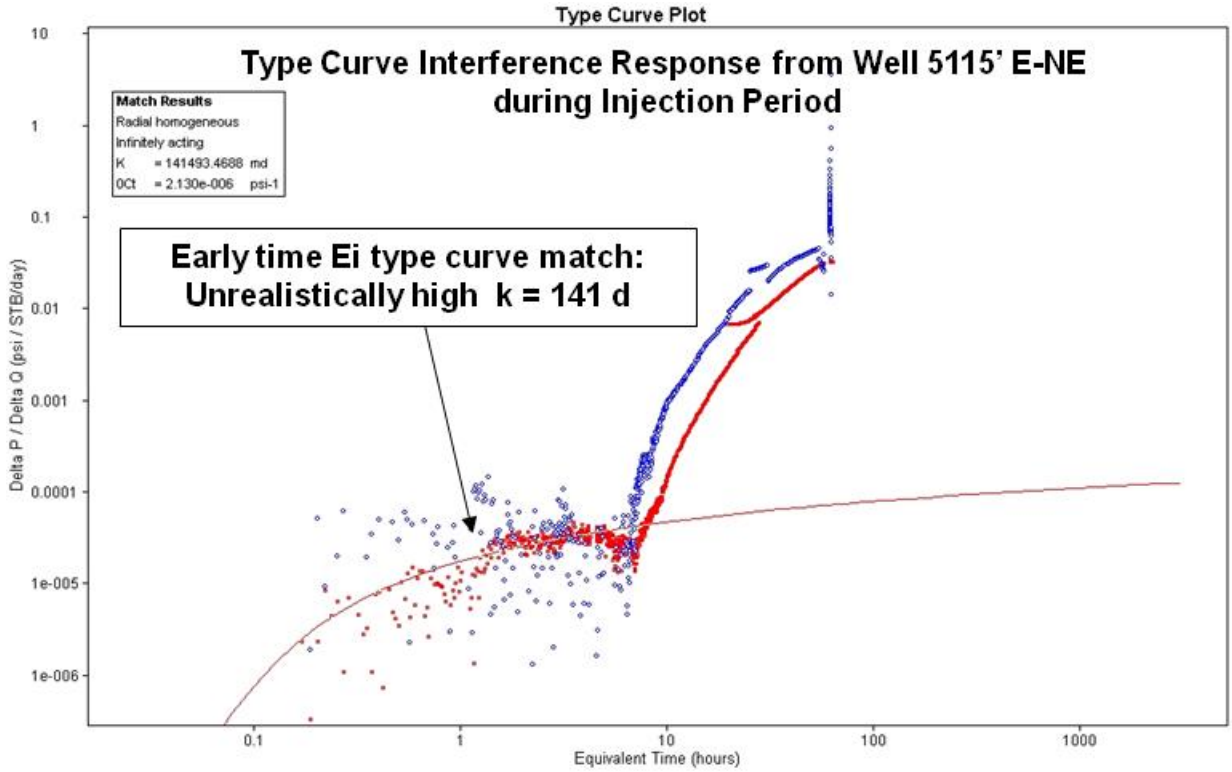


FIGURE I- 11: TYPE CURVE MATCH OF LATE TIME INTERFERENCE PRESSURE RESPONSE AT WELL LOCATED 5115' E-NE

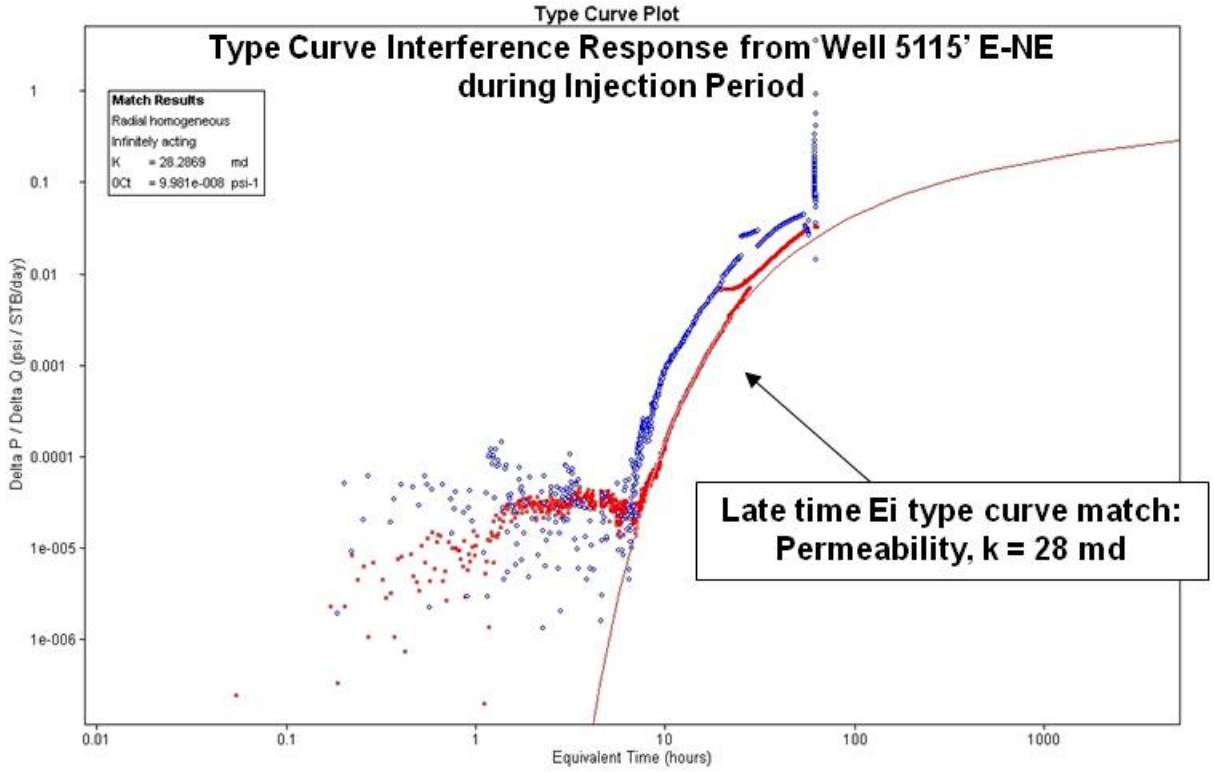


FIGURE I- 12: TYPE CURVE MATCH OF INTERFERENCE PRESSURE RESPONSE AT WELL 6006' E-NE

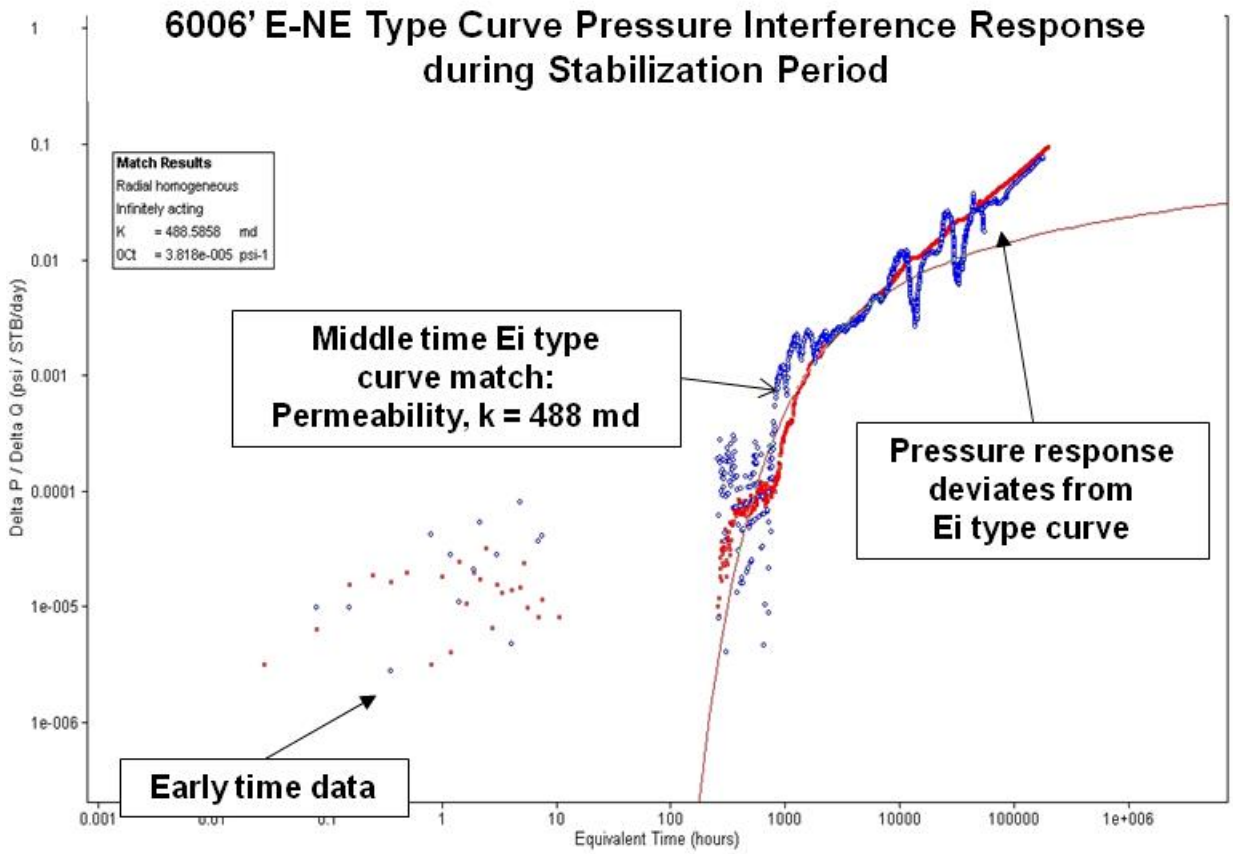


FIGURE I- 13: MONTHLY DISPOSAL VOLUMES AND MEASURED STATIC RESERVOIR PRESSURES FOR MONITORED DISPOSAL WELL

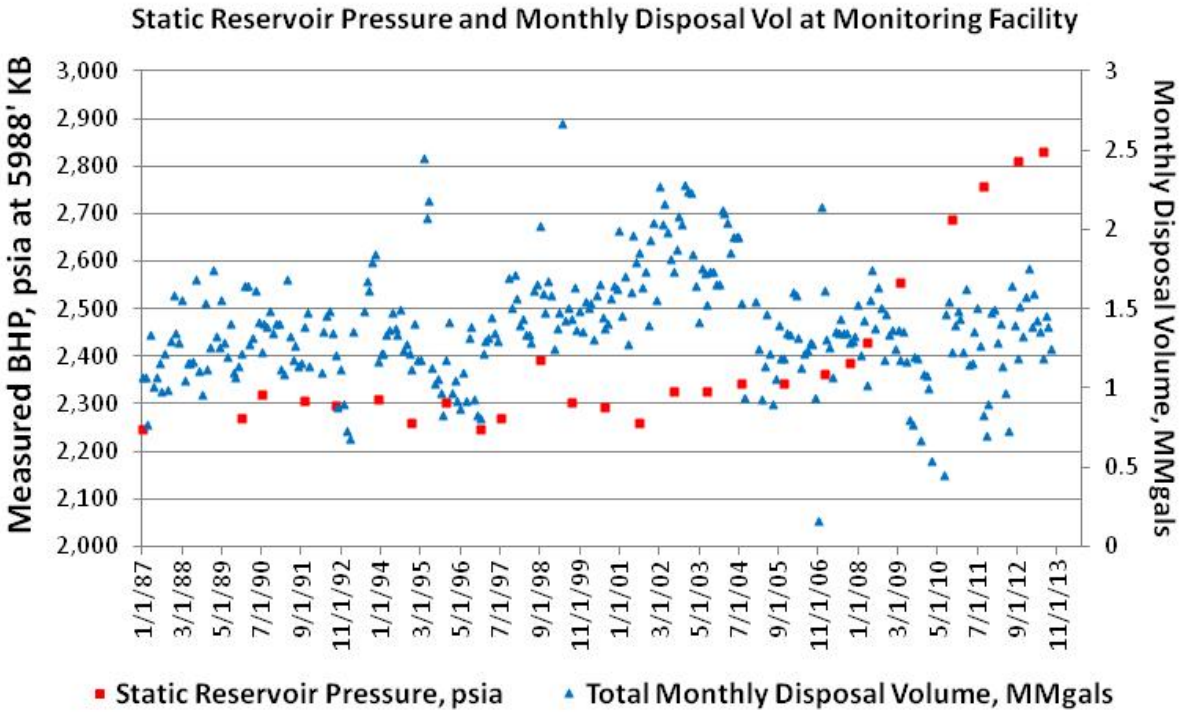


FIGURE I- 14: LOCATION OF OFFSET WELLS FROM MONITORED DISPOSAL WELL

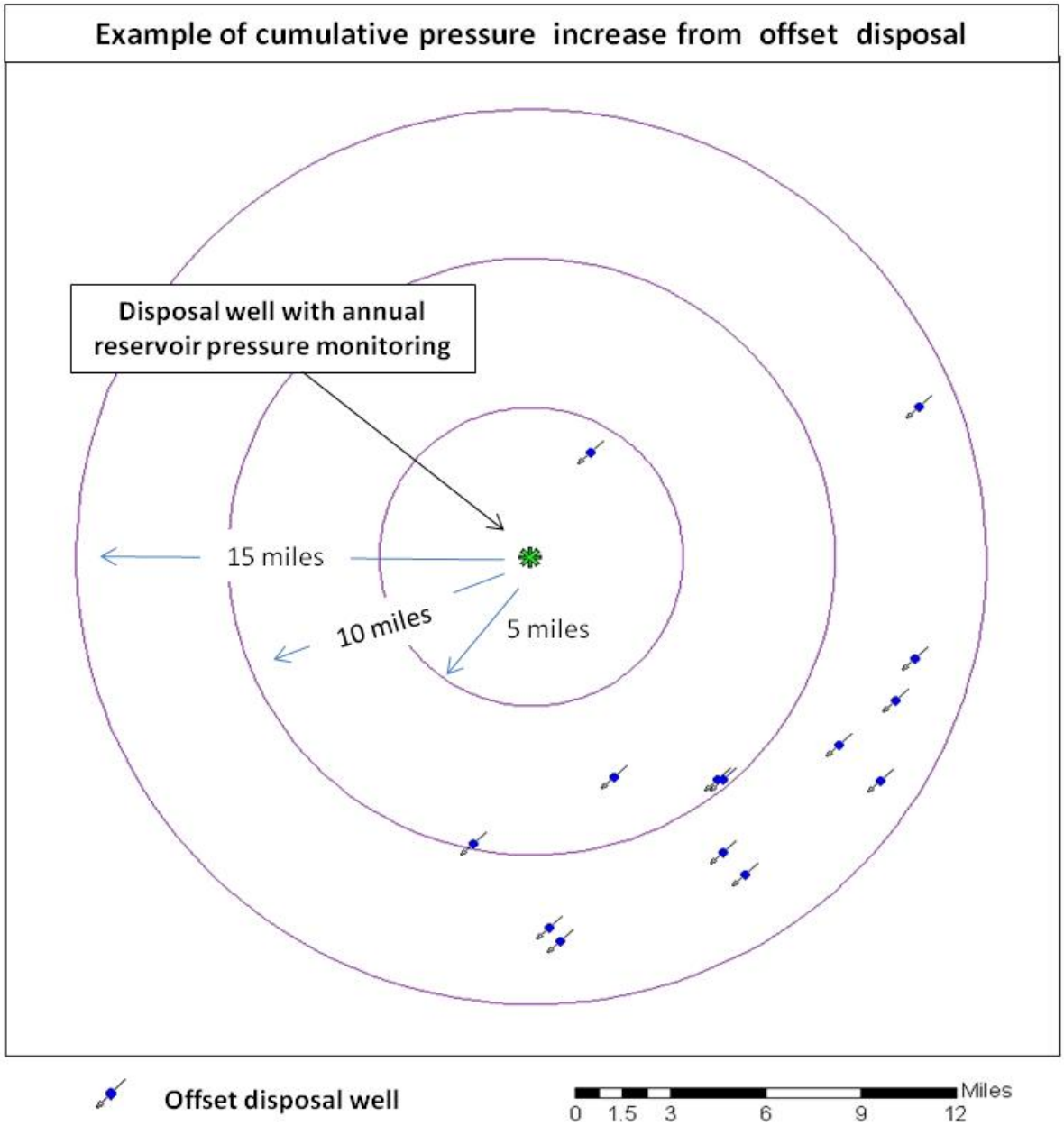


FIGURE I- 15: MONTHLY ACTIVE WELL COUNT FOR EXAMPLE AREA INCLUDING MONITORED DISPOSAL WELL

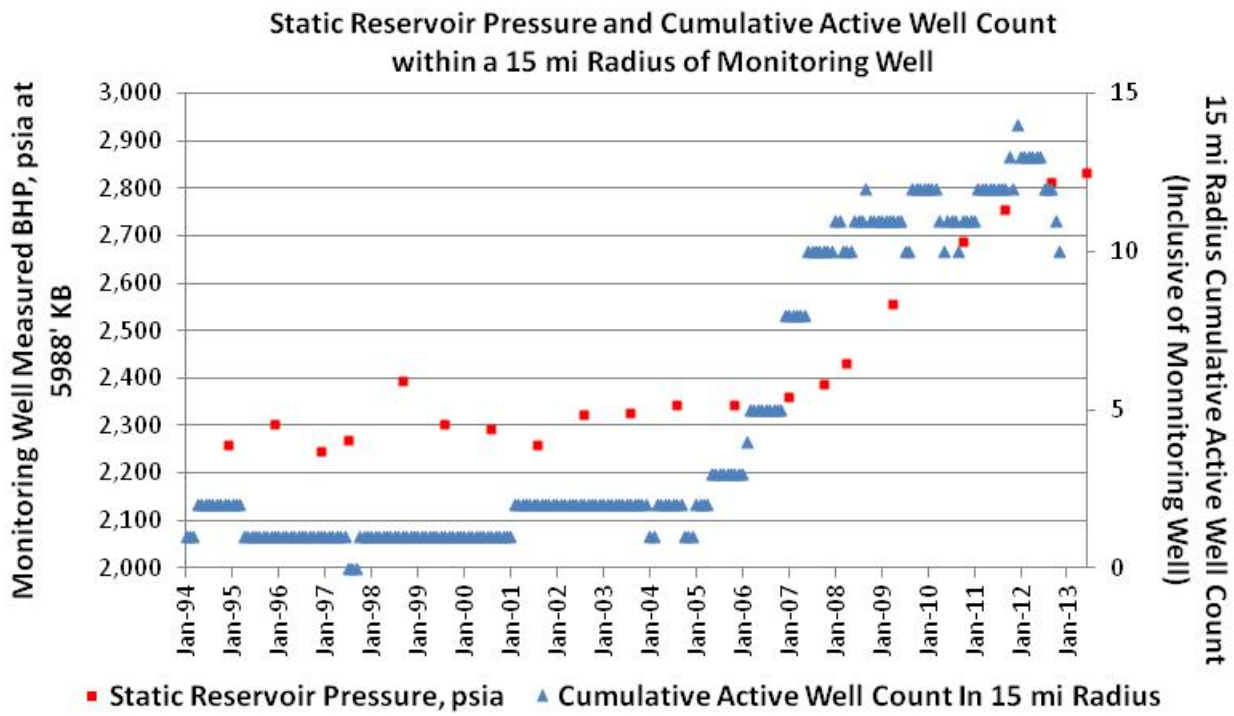
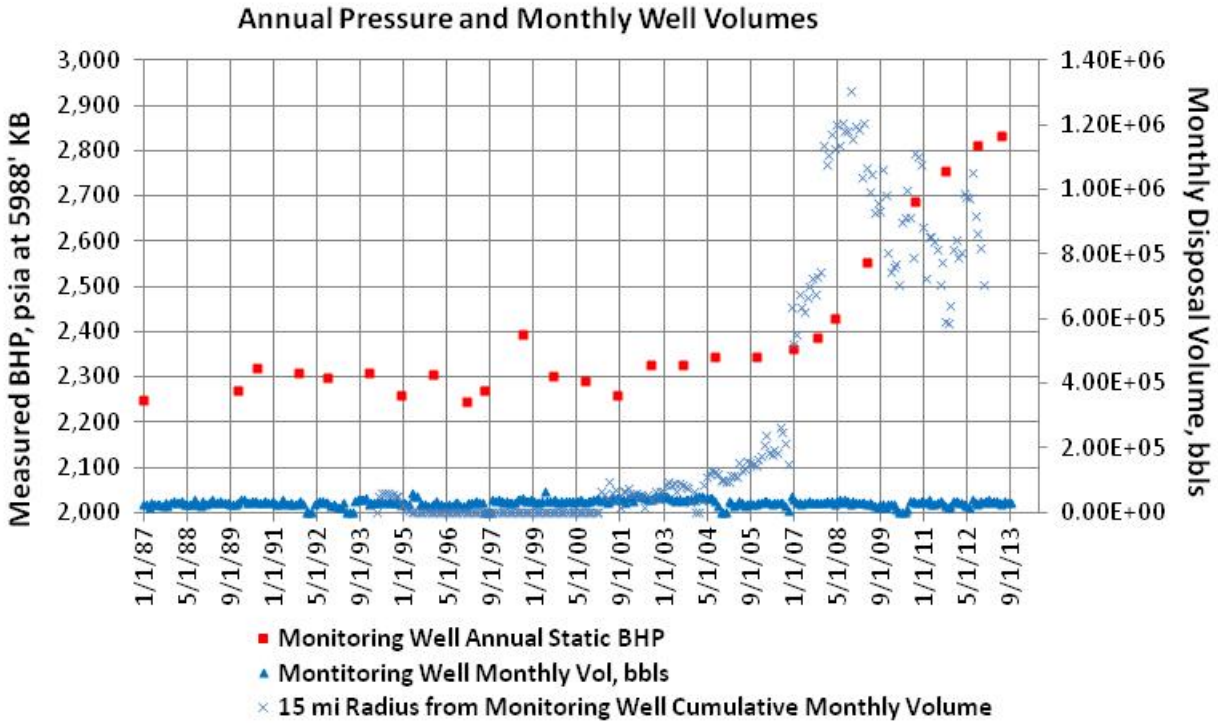


FIGURE I- 16: MONTHLY DISPOSAL VOLUMES WITHIN A 15 MILE RADIUS AND MONITORED DISPOSAL WELL RESERVOIR PRESSURES



APPENDIX J: PARADOX VALLEY, COLORADO

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Figure J-1: Injection-Induced Seismicity and Injection Rates J-3
Figure J-2: Injection Rates and Pressures J-4
Figure J-3: Earthquake Clusters J-5

INTRODUCTION

The U.S. Bureau of Reclamation runs a deep, high-pressure, Class V disposal well in Paradox Valley, Colorado. This operation is part of the Colorado River Basin Salinity Control Project designed to remove near-surface brine and limit saline flow into the Dolores River. Disposal is into the Mississippian carbonate and the upper Precambrian granite, i.e., basement rock. Prior to completion of the well, a 10-station seismic network was installed in the area. Upgrades are made to the seismic network and the coverage area has been enlarged as necessary.

Figure J-1 contains two figures; the top shows the number and magnitude of events over time, versus the distance from the disposal well. The lower figure shows the injection rate over time. Only one earthquake was recorded prior to the 1991 start of injection. Numerous earthquakes followed the start-up of disposal operations, injection and stimulation tests (Phase I injection). Project reports highlight the apparent correlation between close earthquakes (near-well at ≤ 4 km from the disposal well) and initial tests. Relatively continuous injection (Phase II injection) did not begin until July 1996. An earthquake cluster (between 6 and 8 km northwest of the disposal well), accompanied this activity in addition to the near-well cluster. In response to a third northern cluster of earthquakes (<13 km), along with near-well magnitude 3.5 and 4.3 events, the injection rate was reduced in 2000 (Phase III injection) and included a biannual 20-day shutdown. This method was initially effective in reducing the earthquake frequency and magnitude.

In January 2002, (Phase IV injection) the injectate mix changed from 70 percent brine and 30 percent fresh Dolores River water to 100 percent brine. Figure J-1 shows an M3–M3.5 earthquake occurring in the second distance cluster at about this time, followed by a >M3.5 event near the well around the end of 2003. Figure J-2 illustrates the injection rates, surface pressures and bottomhole pressures, in the top, middle, and lower plots, respectively. The lower plot shows an immediate increase in downhole pressure followed the conversion to all brine. The >M3.5 event correlates with earlier M3.5 events when downhole pressure exceeded an apparent

downhole pressure threshold. In 2004 a southeast cluster of earthquakes (see Figure J-3) started, which increased in frequency in 2010.

More than 5,800 earthquake events have occurred since initial injection activities began in the area. There is minimal geosciences information along the northern edge of the valley. The Precambrian basement has not yet been modeled. The Precambrian earthquakes in the center of the valley are not well located. Currently a search for a second disposal well location is underway (Block et al., 2012).

CITATIONS

Block, L., W. Yeck, V. King, S. Derouin, and C. Wood, 2012, Review of geologic investigations and injection well site selection, Paradox Valley unit, Colorado: Technical Memorandum No. 86-68330-2012-27, Bureau of Reclamation, Denver, Colorado, 62 p., http://www.coloradoriversalinity.org/docs/CRB_TM_final_reduced.pdf

FIGURE J-1: INJECTION-INDUCED SEISMICITY AND INJECTION RATES

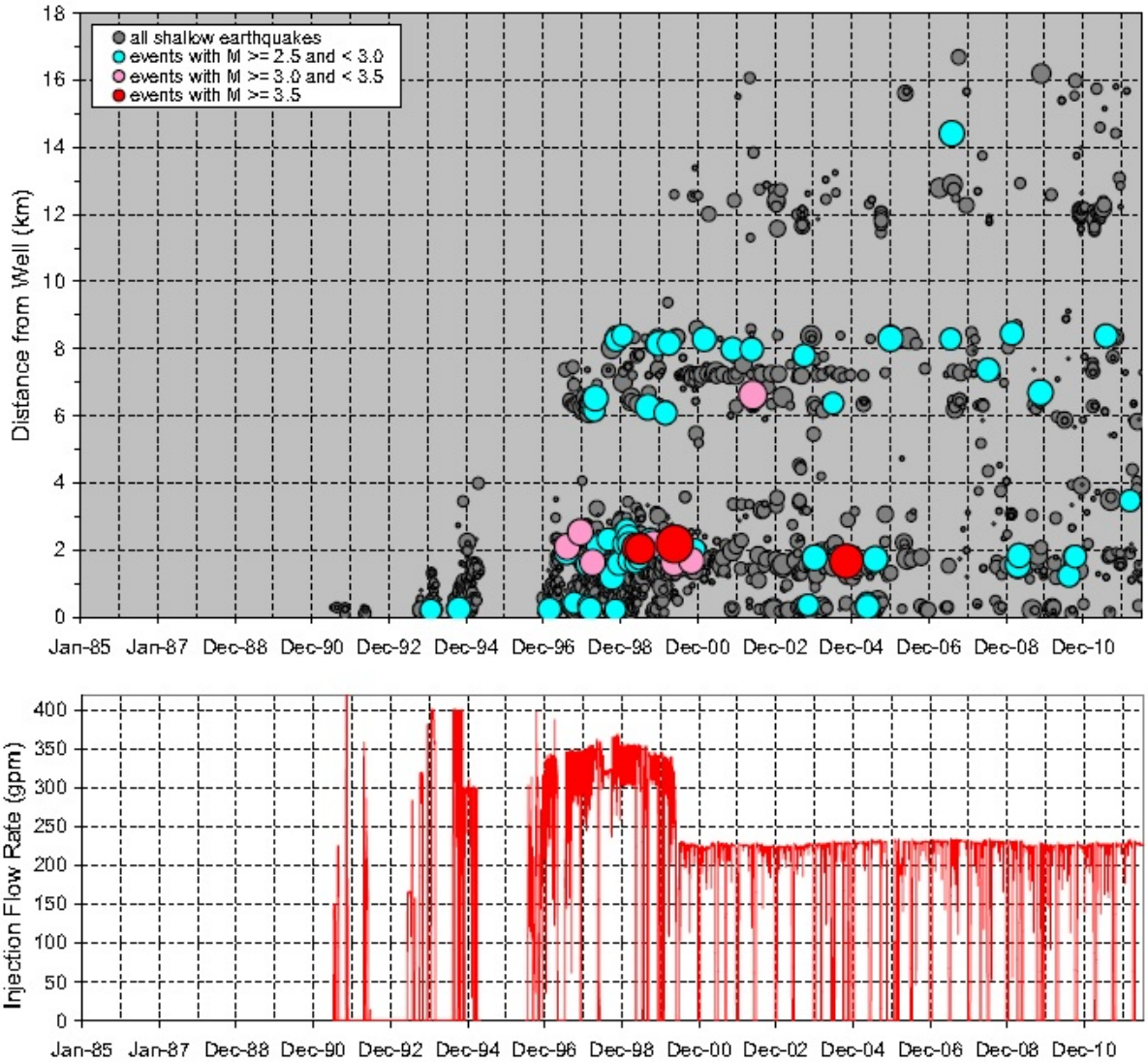

FIGURE J-2: INJECTION RATES AND PRESSURES

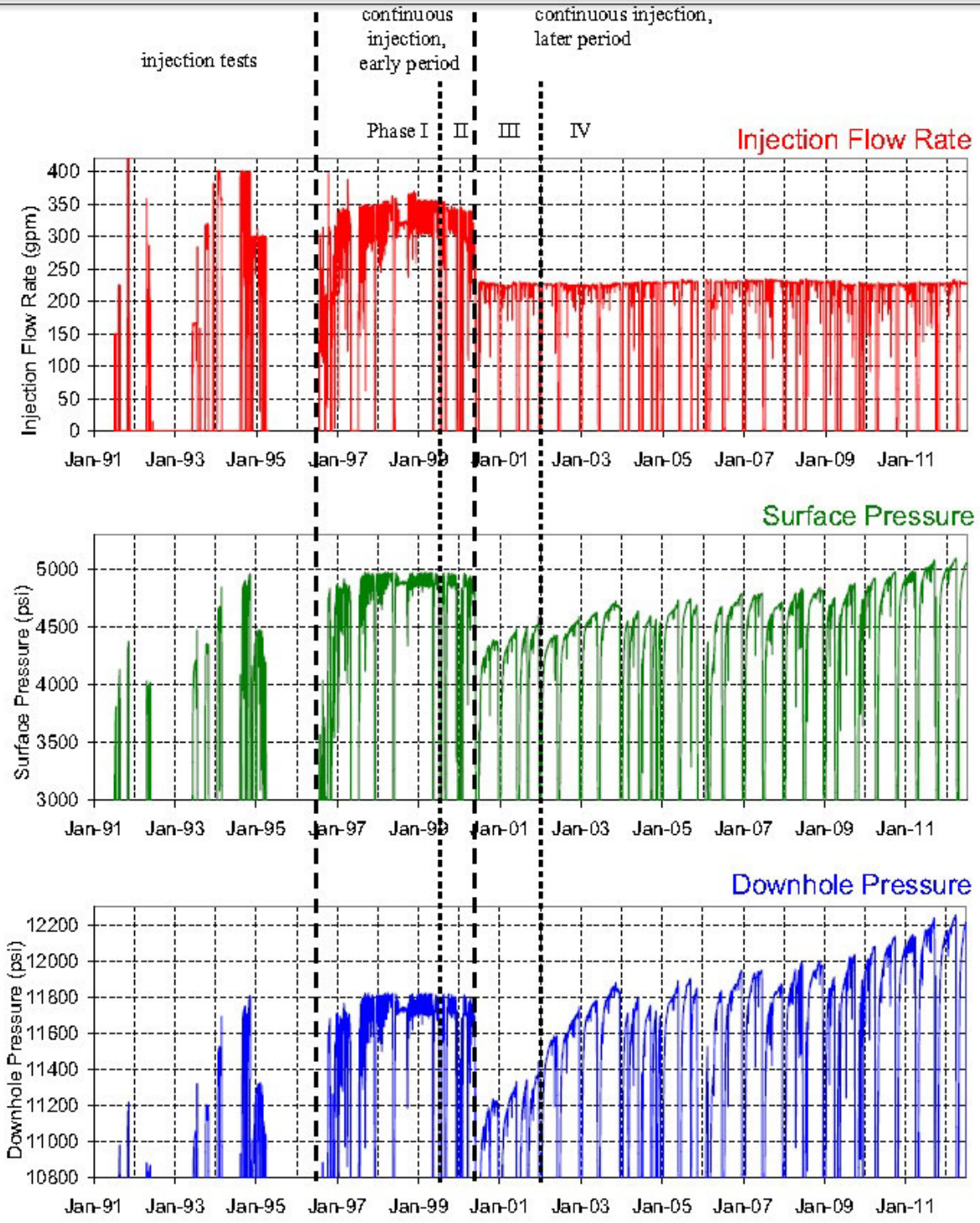

FIGURE J-3: EARTHQUAKE CLUSTERS

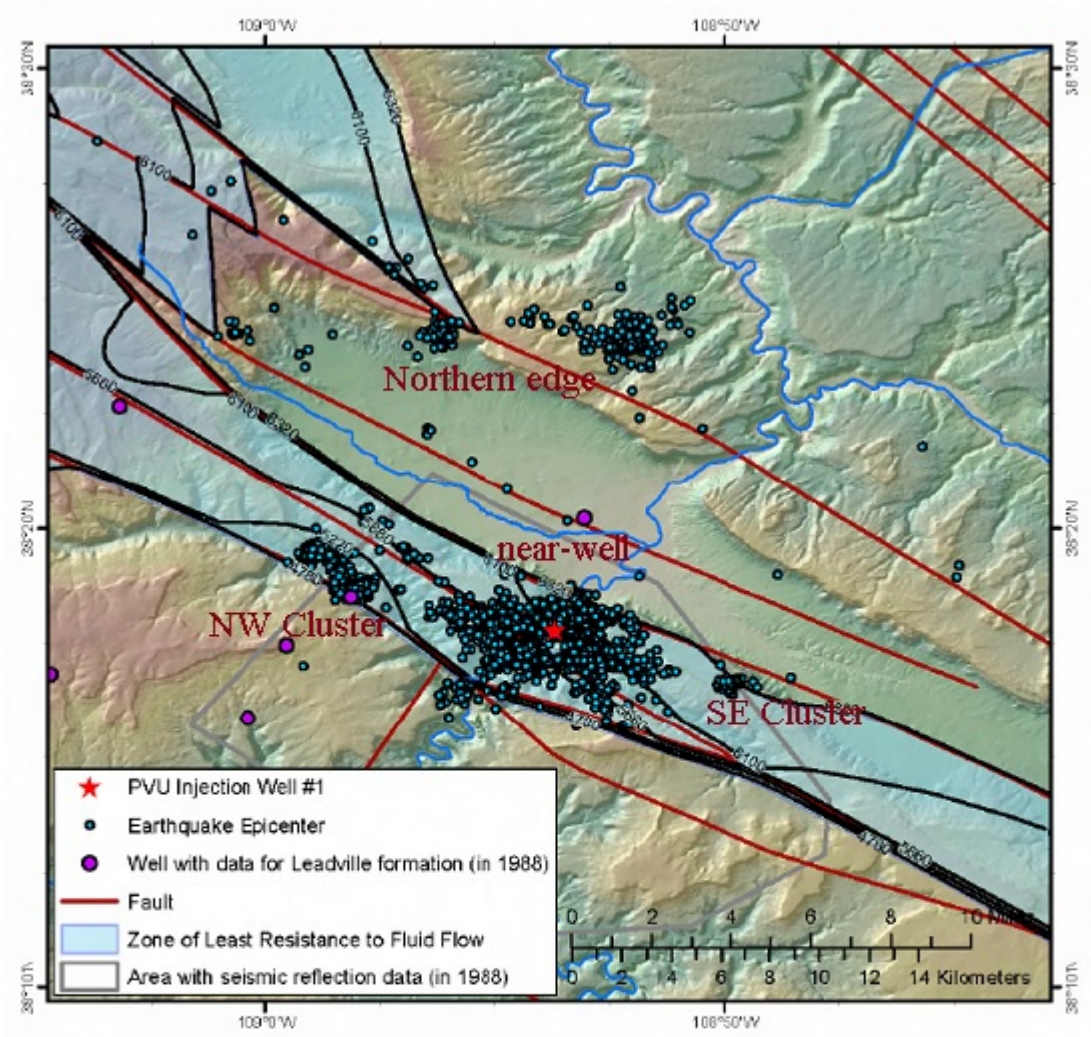

Figure 25: Contour map of hydrostatic pressure within the Leadville formation and predicted area of least resistance to fluid movement and pressure rise from injection into PVU Injection Well #1, from Bremkamp and Harr (1988) (drawing no. 2), and epicenters of shallow earthquakes interpreted to be induced by fluid injection into PVU Injection Well #1. (Fault traces were digitized from drawing no. 1, Bremkamp and Harr, 1988).

APPENDIX K: SUBJECT BIBLIOGRAPHY

Injection-induced seismicity is a rapidly expanding area of research. This list is not intended to serve as a complete resource list. Additionally, websites frequently shift links, so some may become inactive.

Disclaimer K-1
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- Associations & Surveys: Professional Scientific and Engineering K-2
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- Industry Websites on Casing Damage K-3
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DISCLAIMER

Inclusion of an article or website in this appendix does not represent NTW's or EPA's agreement with the conclusion of the article.

Helpful Links

Associations & Surveys: Professional Scientific and Engineering

American Association of Petroleum Geologists, http://www.aapg.org/

Canadian Association of Petroleum Producers, http://www.capp.ca/aboutUs/mediaCentre/NewsReleases/Pages/Seismicitynaturalgasproducerstakestepstoensurecontinuedsafehydraulicfracturingoperations.aspx

Canadian Society of Exploration Geophysicists: Microseismic User Group (MUG), http://cseg.ca/technical/category/mug/

Oklahoma Geologic Survey, http://www.okgeosurvey1.gov/pages/research.php

Seismological Society of America, http://www.seismosoc.org

Society of Petroleum Engineers, http://www.spe.org/index.php

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Real-time & Historical Earthquake Information, http://earthquake.usgs.gov/earthquakes/?source=sitenav,ast Modified: September 25, 2013.

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NASA Earth Fact Sheet, http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html

Dictionary, http://www.dictionary.com,

Industry Websites on Casing Damage

http://www.terralog.com/casing_damage_analysis.asp

Useful Publisher or Other Search Engines (abstracts usually free)

AAPG Datapages, http://archives.datapages.com/data

GeoScience World, www.geoscienceworld.org/search

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Peer Reviewers' Requested Additions: Within Scope

The following articles were added at the request of various members of the peer review group. Only articles in peer-reviewed publications are included. Some may already have been listed.

http://www.gwpc.org/resources/publications; contains multiple publications noted by peer reviewers

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APPENDIX L: DATABASE INFORMATION

Table L-1: Earthquake Catalogs..... L-2
Table L-2: Earthquake Catalog Events for Central Arkansas Case Study L-4

CATALOGS OF EARTHQUAKE EVENTS

The largest U.S. database of earthquake events is maintained by the Advanced National Seismic System (ANSS). The National Earthquake Information Center (NEIC) maintains several other data catalogs. Both ANSS and NEIC programs are under the U.S. Geological Survey (USGS). There is limited consistency between the various groups on coverage areas, detection thresholds, or magnitude determinations. Table L-1 provides a reference to the primary earthquake catalogs. State geologic agencies and universities may also collect and/or host earthquake information on their websites. The catalogs generally include an indication of the event location reliability. The main ANSS composite catalog, hosted by the Northern California Earthquake Center at the University of California at Berkeley, contains events from multiple sources and time periods, but strips duplicate listings.

As an example of catalog coverage, Table L-2 shows the number of events recorded in the search area of the central Arkansas area case study (discussed in detail elsewhere in this report). Care must be taken to avoid duplication when using multiple sources of data. Not all matching events have the same calculated epicenter and depth. It is also noted that depth refinements to preliminary NEIC data have been incorporated in the ANSS catalog but not in the NEIC Preliminary Determination Earthquake (PDE) catalog.

TABLE L-1: EARTHQUAKE CATALOGS

Source	Coverage (Years)	Area	Comments/Caveats
International Seismological Centre[34]	1904- present	The official world catalog	
ANSS Catalog[35][36] (hosted by NCEDC)	1898 - present	Composite across the USA	M1.0 and greater
ANSS Comprehensive Catalog (ComCat)	Combined from 2/2/2013	Composite of U.S. contributing networks	Includes moment tensors, plus (see APPENDIX M, Task 1)
Center for Earthquake Research and Information (CERI) Catalog aka New Madrid Earthquake Catalog[37]	1974 - present	New Madrid Seismic Zone and surrounding regions	
NEIC (USGS) Catalog[38]	SRA: 1350-1986	Eastern, Central & Mountain States	Very few magnitudes given
	USHIS: 1568-1989	Significant U.S. quakes	Felt or M4.5 and greater
	PDE: 1973- present	USA	Updated file from PDE-Q
	PDE-Q: 1973- present	USA (most recent)	Very preliminary locations
	Real Time: Last 7 days	USA	≥ M1.0; interactive map locations ; with accuracy range
	Alert: current	USA and World	E-mail notification available
National Center for Earthquake Engineering Research (NCEER) Catalog[39]	1627 - 1985	Central and Eastern United States	Used in national hazard map creation
Array Network Facility ANF/ANFR[40]	2009 - present	US Array Network	Contains many surface induced events
IRIS[41] SeismiQuery	1960 - present	US & world	USGS and other networks
Harvard Centroid Moment Tensor (CMT) Catalog[42]	1976 - present	Global	Tensor calculations for > M5

[34] ISC: http://www.isc.ac.uk/iscbulletin/search/bulletin/interactive/

[35] ComCat: http://earthquake.usgs.gov/earthquakes/search/

[36] ANSS: http://quake.geo.berkeley.edu/cnss/

[37] CERI/New Madrid Catalog: http://www.ceri.memphis.edu/seismic/catalogs/cat_nm.html

[38] NEIC: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

[39] NCEER: http://www.ceri.memphis.edu/seismic/catalogs/cat_nceer.html

[40] IRIS EarthScope Data: http://www.iris.edu/earthscope/usarray/ or http://anf.ucsd.edu/recenteqs/

[41] IRIS: http://ds.iris.edu/SeismiQuery/ & http://ds.iris.edu/wilber3/find_event

[42] The Harvard CMT (Centroid Moment Tensor) moved to Lamont-Doherty in 2006. It is now called the Global CMT Project. See http://www.globalcmt.org/

Source	Coverage (Years)	Area	Comments/Caveats
Northern California Earthquake Data Center (NCEDC)[43]	1910 - 2003 1967 - present	Northern and Central CA; plus additional monitors in Nevada	Operated by USGS since 1967.
Southern California Earthquake Data Center (SCEDC)[44]	1977 - present	Southern CA	

[43] NCEDC: http://www.ncedc.org/ncedc/catalog-search.html Try also Berkeley Seismological Laboratory: http://seismo.berkeley.edu/

[44] SCEDC: http://www.data.scec.org/

TABLE L-2: EARTHQUAKE CATALOG EVENTS FOR CENTRAL ARKANSAS CASE STUDY

Catalog	Common Events with ANSS	Unique Catalog Events	Total Events
ANSS: Central and Eastern U.S.	-	1533	1533
NEIC: SRA[45]	0	0	0
National Center for Earthquake Engineering Research (NCEER)	15	1	16
NEIC: USHIS[46]	1	0	1
Center for Earthquake Research and Information (CERI)	1523	4	1527
NEIC: PDE & PDE-Q	267	12	279
Total unique Arkansas events		1549	

[45] Eastern, Central and Mountain States of United States (1350-1986)

[46] Significant U.S. Earthquakes (1568-1989)

APPENDIX M: USGS COLLABORATION

Scope of Work for USGS and EPA Project on Induced Seismicity Acitvity for Class II Disposal Wells M-3
Evaluate Potential Risks of Seismic Events due to Injection-Well Activities M-5
Task 1. USGS Data Products for Earthquake Hazards M-6
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Figure M-M-1: Shear Strength of the Crust Based on Laboratory Friction Experiments for the Upper Crust (Upper 14 to 15 km) and Experiments at High Temperatures and Pressures for the Lower Crust where Deformation is Ductile* M-14

Through an interagency agreement, EPA was able to employ the expertise of U.S. Geological Survey (USGS) staff for this project as outlined in the scope of work[47] below. The USGS prepared a report titled, *Evaluate Potential Risks of Seismic Events due to Injection-Well Activities.* The report included a guide on the USGS earthquake hazards and seismic activity maps aimed at non-geophysicists (Underground Injection Control (UIC) scientists and engineers). The report also

[47] Task 3 was dropped from the scope of work. The timeframe for Task 4 has been extended.

provided USGS insight on the relationship between subsurface stress fields and the likelihood of induced seismicity.

The USGS Task 4 was to update the *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001*[48] publication, but the draft update was not finalized and therefore not included.

[48] Meremonte, M. E., J. C. Lahr, A. D. Frankel, J. W. Dewey, A. J. Crone, D. E. Overturf, D. L. Carver, and W.T. Bice, 2002, Investigation of an earthquake swarm near Trinidad, Colorado, August-October 2001: U.S. Geological Survey Open-File Report 02-0073 [http://pubs.usgs.gov/of/2002/ofr-02-0073/ofr-02-0073.html], accessed December 5, 2011.

Scope of Work for USGS and EPA Project on Induced Seismic Activity for Class II Disposal Wells

Objective: Provide support data for EPA's UIC National Technical work group project on induced seismicity from Class II brine disposal well operations.

Background: Numerous publications exist that study the relationship between induced or triggered earthquakes and injection activity. The factors that might influence the occurrence of large damaging earthquakes near Class II disposal wells include (1) large-scale nearby fault(s), (2) high differential stresses at depth, and (3) changes in fluid pressure or stress due to fluid injection. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to enhance strategies for avoiding damaging seismicity events related to Class II disposal wells.

Scope of Work: Through available expertise, complete the following specific work tasks that support the UIC NTW induced seismicity project. USGS and/or procured data will be used and referenced in the UIC NTW final work product. The tasks will necessitate cooperation between EPA and USGS, including incorporating the expertise and experience from EPA UIC geologists and engineers and USGS staff.

Work Tasks

1. Prepare a practical guide on the USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers (non-geophysicists). The document should cover topics such as background information relevant to the two maps, confidence levels and sensitivity of the mapped data. For example:
    a. Describe the epicenter location and hypocentral depth with respect to accuracy of the data. This should include accuracy within both map and depth locations.
    b. Describe the relevance of the earthquake hazard maps for subsurface use.
2. Using technical expertise what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?
3. Incrementally evaluate commercial structure maps on the deepest available horizon for one of the following areas to determine if this type of data can be used as a screening tool. EPA will provide USGS with the structure maps. The evaluation may include, but is not limited to, correlating seismic events and available injection well locations with structural maps. During coordination between EPA and USGS, specific location information will be provided. The following are the generic areas of interest, though EPA may change the priorities.
    a. North Texas Ouachita Thrust front
    b. Arkansas Fayetteville Shale play
    c. West Virginia Braxton County
    d. Colorado Trinidad area
    e. Ashtabula Ohio area

    Depending on the results of the initial pilot study, additional analyses may be performed on more of these areas at a later date.

4. Review *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001* and submit a progress report and final report on updates to this study including identifiers that could have predicted the recent 5.3 earthquake.
5. Provide interim data, final report of conclusions and all work completed.

Milestones

Provide monthly updates

Timeframe

Work and accompanying reports for tasks 1-3 should be completed by December 16, 2011.

A progress report for task 4 should be completed by December 31, 2011, with work on task 4 continuing into 2012. The final report for task 4 should be completed no later than April 30, 2012.

Underground Injection Control Interagency Agreement
EPA IA DW-14-95809701-0

Evaluate Potential Risks of Seismic Events due to Injection-Well Activities

A. McGarr, W. Ellsworth, J. Rubinstein, S. Hickman, E. Roeloffs, and D. Oppenheimer

United States Geological Survey

The Scope of Work for the USGS and EPA project on induced seismic activity for Class II disposal wells includes two tasks:

Task 1: Prepare a practical guide on USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers.

Task 2: Using technical expertise, what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?

The results of USGS work on these two tasks are described in this report.

Task 1. USGS Data Products for Earthquake Hazards

Earthquake Catalog—ANSS Earthquake Catalog

http://www.quake.geo.berkeley.edu/anss/

This is the authoritative earthquake catalog for the United States. It contains the most current information from all of the participating regional networks and the U.S. National Network in the Advanced National Seismic System (ANSS). This catalog can be searched for a given geometric area, over a given time and a given magnitude range. Quarry blasts and earthquakes can also be selected/deselected. Earthquake time, location, magnitude, magnitude type, and parameters relating to how the earthquake location and magnitude were computed (number of stations, travel time error, and source network) are contained in the output of this search. This catalog contains all earthquakes that were detected by the local and regional networks within the United States, including both natural and induced earthquakes—if quarry blasts are not turned off, they will be included as well. This catalog reflects historical seismicity, which may be used as a guide to where we expect future seismicity, but there is always a possibility that earthquakes will occur where previous earthquakes have not. The catalog can be searched for earthquake-specific areas using the search tools at http://www.ncedc.org/anss/catalog-search.html. This catalog is updated in near-real time.

Caveats

- This earthquake catalog is not uniform. In some regions, the catalog begins much earlier than in others, because seismometers were deployed earlier.
- Detection capabilities are not uniform. As a seismic network becomes denser with time, it is able to record smaller earthquakes. This also means that regions with dense networks will see smaller earthquakes than regions with more sparse seismic networks.
- Earthquake locations and magnitudes are of varying quality. As the number of instruments close to the earthquakes increases, location and magnitude estimates become more accurate. This means that location and magnitude quality vary from region to region. Location and magnitude quality also vary over time within a region as the number of instruments increase.
- Earthquake magnitudes are computed a number of different ways depending on the earthquake size and number of nearby stations. These magnitudes are often similar, but not always the same.
- ANSS also maintains a webpage with caveats about their catalog: http://www.ncedc.org/anss/anss-caveats.html

An example of how increasing station density improves earthquake detection is found at the end of this document in the USArray section.

Earthquake Databases

http://earthquake.usgs.gov/earthquakes/search/

A variety of additional earthquake catalogs covering the U.S. are available online and can be used to search for both recent and historical earthquakes. An introduction to earthquake databases and catalog sources is available at . Special attention should be paid to the explanation of differences between the various catalogs.

Online search tools that can be customized to select earthquakes in different geographic regions and over different time and magnitude ranges are available at .

Caveats

- These earthquake catalogs are not uniform in either space or time. In some regions, the catalog begins much earlier than in others because seismometers were deployed earlier.
- Earthquake smaller than magnitude 1 are not included in these catalogs.
- In most areas, the catalog is complete since 1973 for earthquakes of magnitude 3 or larger.
- The accuracy of the earthquake locations varies considerably. In most areas outside of California, Nevada, Oregon, Washington, and Utah, earthquake epicenters may be in error by as much as 6 miles, on average. Exceptions apply where there are local networks, such as in the New Madrid Seismic Zone.

National Seismic Hazard Map

http://earthquake.usgs.gov/hazards/products/

The National Seismic Hazard Map delineates the probability of strong shaking across the United States from natural earthquakes. These maps do not assess the risk of shaking owing to induced earthquakes. These are probabilistic maps and do not refer to specific earthquakes. Instead, the maps provide information on the strength of earthquake shaking that is unlikely to be exceeded over a given period of time.

A guide to the hazard maps can be found at:
http://earthquake.usgs.gov/hazards/about/basics.php

Frequently Asked Questions about Hazard Maps:

http://www.usgs.gov/faq/?q=taxonomy/term/9843

The maps are derived from knowledge of active faults, past earthquakes, and information on how seismic waves travel through the Earth. As indicated above, our knowledge of past earthquakes and faults is incomplete, which means that strong shaking due to earthquakes may still occur in regions with low probabilities. It is less likely to occur in these regions, but it still can happen.

The ground motions reported in these maps are estimated for the surface. Ground motions decrease with depth below the surface. Shaking is strongest in the area immediately surrounding an earthquake.

Earthquake Probability Calculator

This tool allows you to compute the probability of an earthquake occurring within a specific radius of a specified location. The probabilities are derived from the National Seismic Hazard Map described above. The tool produces two products:

1. A map surrounding the location specified, with color contours giving the probabilities of an earthquake larger than or equal to the magnitude specified by the user (minimum magnitude 5.0)
2. An optional text report describing the annual rates of earthquakes of different sizes.

It is important to note that, where the probability on the maps is shown to be 0.00, this does not mean that there will not be an earthquake there. When a region falls into the 0.00 category, it means that the probability of an earthquake is less than 1% during the time period specified.

By selecting the Text Report, it is possible to change the radius from the default value of 50 km. The Text Report gives information for earthquakes that fall within magnitude bins (for example, between 7.35 and 7.45): the annual rate at which an earthquake in that bin is expected to occur, the annual rate at which an earthquake within that bin or larger will occur, and probabilities of an event within that magnitude bin and within that bin or larger occurring in the time period specified by the user. The last two quantities can be inverted to determine the average number of years between earthquakes.

Limitations of the Probability Mapping Calculation

The probability is only calculated for events of M5.0 and larger. It is advisable to consider the rates of smaller earthquakes that may be the first evidence that an area is sensitive to injection-

induced earthquakes. Such a calculation can be done using catalog searches but is not currently available as an online tool.

There are no confidence intervals on the probabilities. The values given are annual averages and earthquake rates naturally fluctuate in time. Therefore, as presently written, this application cannot help decide whether the seismicity in the last year, for example, is within the normal range of variation for this site.

The Quaternary Fault and Fold Database of the United States

http://earthquake.usgs.gov/hazards/qfaults/

This database contains information on known faults and associated folds in the United States that are believed to have been sources of M>6 earthquakes during the Quaternary (the past 1,600,000 years). The website includes both static and interactive maps of these geologic structures, with links to detailed references.

This database does not include faults that show no evidence of Quaternary movement. Faults that have had M>6 earthquakes but that do not extend to the surface and/or that have not been recognized at the surface may not be in the database. Only faults believed capable of hosting M>6 earthquakes are included, but earthquakes as small as M5.0 are potentially damaging, especially in the central and eastern U.S.

These considerations mean that, if the site is near a fault in the Quaternary Fault and Fold Database, then the necessary geologic structure exists to host an earthquake of M>6. However, if no fault in the database is near the site, it does not necessarily mean that no such fault is present.

New faults are continually being discovered, often as they reveal themselves by earthquake activity. Several years or more may pass between initial recognition that a fault is present, documentation in peer-reviewed literature that the fault is aerially extensive enough to produce a significant earthquake, and incorporation of the fault into the database. Changes to the Quaternary fault database are incorporated into the updates to the National Seismic Hazard Maps that occur every 6 years.

USArray—An Example of Improved Detection Capabilities From Increased Station Density

http://www.usarray.org/

As of this writing, a large seismic array of 400 instruments is moving across the conterminous U.S.

This array, called USArray, is operated by the Incorporated Research Institutions for Seismology (IRIS) and is funded by the National Science Foundation as part of the EarthScope Program. During the 18 months that it takes for the USArray to pass by any particular location, the density of seismic stations is temporarily increased to one station approximately every 70 km, placing a seismometer within about 35 km of every point within the footprint of the array. This higher station density makes it possible to detect and locate earthquakes with M≥2 in most areas and provides data that can be used to reduce the location uncertainty.

When USArray was passing through eastern Colorado and New Mexico from late 2008 to early 2010, several hundred events were detected that were not initially identified by the USGS. Many of these earthquakes lie within or near the coal-bed methane field west of Trinidad, CO.

The Oklahoma Geological Survey has recently used data from USArray to study earthquakes in Garvin County, Oklahoma, and their possible association with shale gas stimulation activities in the Eola Field (Holland, 2011). This report illustrates the potential of improved seismic monitoring for answering basic questions about the association between earthquakes and fluid injection activities. It also draws attention to the challenges of drawing firm conclusions when the historical context of the activity is poorly known and poorly resolved. The same general conclusions can be drawn from the study of earthquakes near Dallas-Fort Worth Airport (Frohlich, C., and others, 2011).

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Frohlich, C., Hayward, C., Stump B., and Potter, E., 2011, The Dallas-Fort Worth earthquake sequence—October 2008 through May 2009: Bulletin of the Seismological Society of America, v. 101, p. 327–340.

Holland, A., 2011, Examination of possibly induced seismicity from hydraulic fracturing in the Eola Field, Garvin County, Oklahoma: Oklahoma Geological Survey Open-File Report F1-2011, 31 p.

The online tools described here are products of the U.S. Geological Survey, but no warranty, expressed or implied, can be provided for the accuracy or completeness of the data contained therein. These tools were not developed for the specific purpose of assessing the potential for induced seismicity and are not substitutes for the technical subject-matter knowledge.

Task 2. Deep Stress Fields and Earthquakes Induced by Fluid Injection

Executive Summary

The purpose here is to explain what we know about deep stress fields and how this might influence the likelihood of earthquakes induced by injection well activities. The available evidence indicates that whether the tectonic setting is active (for example, near the San Andreas

Fault in California) or inactive (for example, central or eastern United States), activities that entail injection of fluid at depth have some potential to induce earthquakes. This does not imply, however, that all injection-well activities induce earthquakes or that all earthquakes induced by injection activities are large enough to be of concern. Indeed, most injection wells do not appear to cause earthquakes of any consequence. The differences between the small percentage of wells that induce noticeable earthquakes and those that cause negligible seismicity are poorly understood. Thus, it is necessary to measure the response of the rock mass to injection to estimate the likelihood that a particular injection well will contribute to the local seismicity. An effective way to do this is seismic monitoring, using local networks that are capable of recording small-magnitude events. Furthermore, to evaluate the likelihood of inducing damaging earthquakes on large-scale, pre-existing faults, information is also needed on the geometry of potentially active faults in relation to the orientations and magnitudes of stresses at depth. This information can be obtained from network observations of ongoing micro-seismicity (if present), borehole stress measurements, and geophysical and geological investigations of fault geometry and fault-slip history.

Even in the absence of detailed information on stresses and fault geometry for a particular site, some useful generalizations can be made on the deep stress field. These generalizations are based on borehole stress measurements made around the world at depths of as much as 8 km, in conjunction with earthquake, geologic, and laboratory studies:

1. The stress field can be described in terms of three principal stresses that are oriented perpendicular to one another. To a good approximation, one of these principal stresses is vertical and the other two are horizontal.
2. The vertical principal stress is readily estimated because, at a given depth, it is due to the weight of the overlying rock mass.
3. The state of stress falls into three categories, depending on the relative magnitudes of the three principal stress regimes: normal, strike-slip, and reverse faulting, for which the vertical principal stress is the maximum, intermediate, or minimum principal stress, respectively. Studies of earthquake focal mechanisms, borehole stress indicators, and active faults have revealed the orientation of the principal crustal stresses at a broad, regional scale over most of the United States.
4. Stress measurements made in boreholes indicate that the horizontal principal stresses generally increase linearly with depth, similarly to the vertical principal stress, but sometimes with significant local perturbations.
5. For a given state of stress and depth, borehole stress measurements are generally consistent with laboratory friction experiments, which suggest that stresses are limited by the strength of the crust.

6. Observations that earthquakes, natural or man-made, may be induced by relatively small stress changes support the idea that the crust is commonly close to a state of failure.

INTRODUCTION

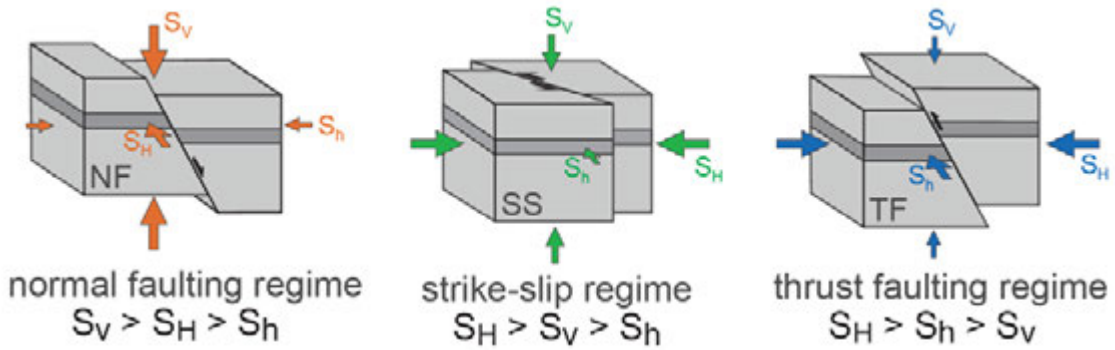
Of the approximately 144,000 Class II injection wells in the United States that inject large quantities of brine into the crust, only a small fraction of these wells induce earthquakes that are large enough to be of any consequence. In spite of their small numbers, these few cases raise concerns about the potential for significant damage resulting from larger induced earthquakes. Accordingly, it would be useful to have some guidelines concerning the likelihood that a particular well will cause significant earthquakes. The intent of Task 2 is to investigate the possibility that the deep stress field can be estimated from surface data. If so, then the next question is whether this stress information can be used to estimate the likelihood of substantial induced seismicity.

STATE OF STRESS

From information already available, we know the deep stress field to some extent. The stress field can be described as three principal stress components orthogonal to one another, with one component oriented vertically, perpendicular to the earth's surface, and the other two oriented horizontally. Factors including topography and geologic structure can alter these principal stress directions somewhat, but not on a large scale. The vertical principal stress at a given depth is, to a good approximation, the product of depth, gravity, and the average density between the surface and the point of interest. Because the approximate density structure of the crust is known nearly everywhere, the vertical principal stress can be readily estimated. Estimating the horizontal principal stress magnitudes requires more information, including knowledge of the local tectonic stress regime.

Surface data from seismograph stations or from observations of active faults and other stress indicators can reveal the tectonic stress regime, at least on a regional scale. This stress regime falls into three categories: normal faulting (vertical principal stress is maximum), strike-slip faulting (vertical principal stress is intermediate), or reverse faulting (vertical principal stress is minimum) (Figure). Earthquake focal mechanisms determined from ground motion recorded at seismograph stations indicate the stress regime wherever earthquakes occur, and, if properly analyzed, can provide valuable information on stress orientations (for example, Hardebeck and Michael, 2006). Geologic investigations of active faults, as well as geodetic measurements of crustal strain accumulation, provide similar information. Accordingly, from these sorts of investigations, which can be made from the surface, we know the regional tectonic stress

FIGURE M-1: SCHEMATIC DIAGRAM SHOWING TECTONIC STRESS REGIMES AND SENSE OF FAULT OFFSET IN RELATION TO THE VERTICAL PRINCIPAL STRESS (S_V), THE MAXIMUM HORIZONTAL PRINCIPAL STRESS (S_H), AND THE MINIMUM HORIZONTAL PRINCIPAL STRESS (S_h)*



***FROM WORLD STRESS MAP**

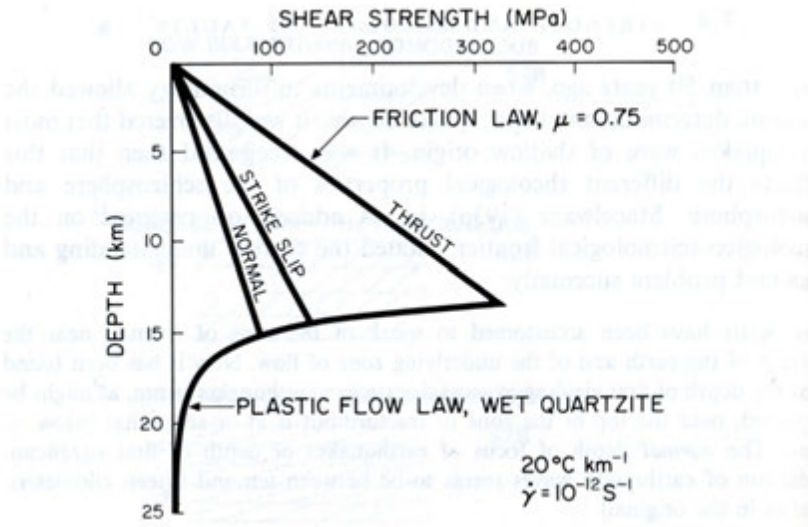
regime nearly everywhere in the United States and for much of the world (see World Stress Map, cited below). However, these observations only tell us the orientations and relative magnitudes of the horizontal principal stresses, and, hence, indicate whether we are in a normal, strike-slip, or reverse faulting stress regime. They do not tell us the absolute magnitudes of the horizontal stresses, which, together with information on stress orientations, determine proximity to failure on optimally oriented pre-existing faults.

MAGNITUDES OF HORIZONTAL STRESSES

The question of the magnitudes of the horizontal stresses is more challenging. Most of our information about horizontal stress magnitudes comes from deep boreholes, using the hydraulic fracturing technique and observations of borehole failure (breakouts and tensile cracks; see Zoback and others, 2003). Additional stress data come from stress relaxation measurements made in deep mines. The deepest measurements were made in the KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) scientific borehole, eastern Bavaria, Germany, and extend to a depth of about 8 km (Brudy and others, 1997). Stress measurements worldwide indicate that the two horizontal principal stresses increase approximately linearly with depth, as is the case for the vertical stress. Moreover, in-situ stress magnitudes have been compared to laboratory experimental friction results (for example, Brace and Kohlstedt, 1980; Townend and Zoback, 2000) to find that the crust appears to be close to a failure state nearly everywhere. This experimental observation is consistent with the idea that the Earth's crust is extensively faulted and can deform by frictional sliding. Moreover, the crust is continually undergoing strain accumulation, at quite a slow rate in tectonically stable regions and at higher rates in tectonically active regions. The result of this long-term strain accumulation is that the crust is always near a failure state and releases strain whenever the yield stress is reached. In a seismogenic region of the crust (much of the uppermost ~15 km), this strain release appears as an earthquake sequence (mainshock and aftershocks). Other evidence in support of the

hypothesis that the crust is near a state of failure nearly everywhere includes the observation that earthquakes can be triggered by remarkably small stress changes imposed on faults (for example, Reasenberg and Simpson, 1992).

FIGURE M-M-1: SHEAR STRENGTH OF THE CRUST BASED ON LABORATORY FRICTION EXPERIMENTS FOR THE UPPER CRUST (UPPER 14 TO 15 KM) AND EXPERIMENTS AT HIGH TEMPERATURES AND PRESSURES FOR THE LOWER CRUST WHERE DEFORMATION IS DUCTILE*



***THE STRENGTH FOR STRIKE-SLIP FAULTING CAN BE ANYWHERE BETWEEN THE REVERSE- AND NORMAL-FAULTING REGIMES. IN THIS FIGURE, SHEAR STRENGTH IS DEFINED AS THE DIFFERENCE BETWEEN THE MAXIMUM AND MINIMUM PRINCIPAL STRESSES (FROM SCHOLZ, 2002).**

The laboratory friction results shown in Figure M-M-1 provide some information about the horizontal stress magnitudes. The line for a normal-faulting regime (labeled “normal”) indicates the difference between the vertical principal stress and the minimum horizontal principal stress. For a reverse-faulting regime, the line shows the difference between the maximum horizontal principal stress and the vertical principal stress. Because the vertical stress can be readily estimated for any depth, as noted before, it is easy, from the information in the figure, to estimate the minimum principal stress for the normal-faulting regime and the maximum principal stress for the reverse-faulting regime. For a strike-slip regime, neither horizontal principal stress can be inferred because the line labeled “strike slip” can fall anywhere between those for normal and reverse regimes. Although generalizations can be drawn about proximity of the crust to failure from this type of analysis, it is important to note that for a particular fault to be activated in response to fluid injection requires that it be well oriented for frictional failure in the local tectonic stress field.

In brief summary, we know that the vertical principal stress can be calculated for any depth, and we also know that laboratory friction experiments (fig. 1) are reasonably consistent with in-situ stress measurements in deep boreholes. These deep borehole measurements, in concert with

the observation that earthquakes can be triggered at low applied stresses, indicates that the crust is near a failure state nearly everywhere. Taken together, this information can be used to estimate, at least approximately, the magnitudes of the maximum and minimum principal stresses at depth that are valid for most rock types for normal- and reverse-faulting regimes; for strike-slip regimes, the maximum and minimum principal stresses fall somewhere in the range between the normal and reverse results. If direct information on stress orientations is lacking for a particular area, then the orientations of the horizontal principal stresses can be estimated by comparison with nearby data that might be available through the World Stress Map Project (http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html).

Conclusions

Because the state of stress in much of the Earth's crust appears to be close to failure, the safest assumption is that any amount of fluid injection could produce some earthquakes. Knowing that it may be possible to induce some earthquakes, however, is not enough to estimate earthquake hazard. It is also important to be able to estimate the maximum likely earthquake that might be induced by a particular injection operation and measure the seismic response of the rock mass to injection. That is, one needs to be able to estimate the distribution of earthquake magnitudes, including the maximum magnitude, likely to result from a given injection activity. To accomplish this goal, it is first recommended to determine the in-situ stress field in relation to the orientation and extent of potentially active faults (fig. 1). Of particular interest would be large faults capable of producing damaging earthquakes. Then, in order to monitor the injection disposal operation, a local seismic network should be installed before commencement of injection that is capable of recording and locating earthquakes over a wide magnitude range. Monitoring induced earthquakes in this way will allow comparison with the injection-time history, as well as with background seismicity. Monitoring seismicity will also help define the subsurface geometry of large-scale active faults that comprise the greatest hazard. With information provided by a seismic network, the contribution of the induced earthquakes to the ambient seismic hazard can be assessed.

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COMMENTS ON EXECUTIVE SUMMARY

BY JEFF BULL, OIL/GAS INDUSTRY

Class	Jeff Bull Oil/Gas Industry
Grouped-Authority Review	1. Pg ES-1, prgh 3, ln 9 The statement that "EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity" begs the question as to why produce the document as a UIC document if "no foul" has ever been committed within the jurisdictional boundaries of the UIC regulations whose sole purpose is to protect underground sources of drinking water as stated on pg 1, prgh 1, ln 1.
Grouped-Authority	2. Pg ES-1 footnote 2: The definition of "significant injection-induced seismic events" to mean "seismic events of magnitude to potentially cause damage or endanger underground sources of drinking water" takes this document outside of the jurisdictional boundaries of the UIC regulations whose sole purpose is to protect underground sources of drinking water as stated on pg 1, prgh 1, ln 1 and not prevent damage, unless the damage pertains to the integrity of the well thus limiting the area of concern to the depth and diameter of the well.
Grouped-Authority	3. Pg ES-2, prgh 1, ln 6-10 In order for the UIC regulations to invoke discretionary authority, the EPA must first make the case that there is a threat to USDW. As indicated in comment 1 above, the "EPA is the unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity"

Class	Jeff Bull Oil/Gas Industry
Clarify	4. Pg ES-2, prgh 2, ln 2-3: the use of "pressure build up" in a general sense without defining why or how the pressure build-up occurred could cause the investigator to reach a false positive as to cause and effect. The injection disposal industry (not just O&G) can see, on a regular basis, the buildup of pressure as a near bore effect related to build up of precipitates associated with water hardness (carbonates) or other chemical reaction that clogs the pores reducing the permeability and causing back pressure. It is for this reason that disposal injection wells may be acidized on occasion to clear the pores and improve injectivity which lowers the injection pressure.
Clarify	a. In this statement and throughout the document, I get the impression that the writer is relying on buildup of pressure as that actual instigator of induced seismicity thru the creation of a fault. That is false because the buildup of pressure to create a fault is hydraulic fracturing and UIC class II disposal wells are permitted with a maximum injection pressure so as to not exceed the fracture pressure.
	b. The document does identify pore pressure as the culprit that triggers a seismic event (thus not an induced seismic event but a triggered seismic event) but fails to describe the complete mechanism and this is understandable because the known mechanism is still a theory and requires lots of research. The theory is based upon the belief that a preexisting fault, is held together by insitu stresses that are disrupted by pore pressure and allow the fault to slip.
Review / Clarify (see also main body)	5. Pg ES-2, prgh 2, footnote 5: The definition of faults of concern needs to be more specific with regard to "significant earthquake" (see Variety and Validity of Approaches – comment 2). The definition also needs to include an expansion of the term "optimally orientated" to include a fault whose orientation is such that the direction of the principal insitu stress is at a 30-50 degree angle to the fault plane. The definition also needs to include a statement that the fault must be critically stressed meaning that there is sufficient stored energy (stress) that should the fault slip, it would generate a seismic event of sufficient magnitude to be detected.
Clarify	6. Pg ES-2, prgh 2, ln 6: The discussion of how to use historic seismic events as an indicator of potential induced seismicity can be argued from both sides. Presence of historic seismicity can be an indicator of an active seismic region or it can be argued that the historic seismic events have released the stored energy thus the potential for a critically stressed fault (See Basic Mechanism of Injection Induced Seismicity – comment 3) to be located in the area is low. Likewise if there is no historic seismicity, it can be argued that the area is dormant or you can argue that the area is just storing up energy creating critically stressed faults that are waiting to be triggered.

Class	Jeff Bull Oil/Gas Industry
Review	7. Pg ES-2, prgh 2, ln 9: "The basic assumption that an accurate history of seismic monitoring in the region of the injection well exists" is flawed. To get the best available seismic history one is going to want to look as far back in history as one can go. At best this is 100 years starting with having to rely on individual people reporting felt events, which was not a reliable reporting process. Active monitoring has only taken place within the last 50-75 years and was located primarily in California and not in the historic oil & gas states of TX, OK, CO, WY, NM. Seismometer coverage within the primary oil and gas states improved when the National Array moved into a state; but then the array moved out within 18-24 months. Some of the states chose to keep some seismometers to bolster their ability to detect seismic events from the array while some did not. So one needs to understand the origin and coverage of the historic data and the fact that the accuracy of the historic data has large error horizontal and vertical ellipses that limits the investigators ability to zero in on potential area of concern around a location suspect of induced seismicity.
Grouped: Scope	8. Pg ES-2, prgh 2, ln 10-12: I agree with the last line. But I believe that "Risk Management Analysis" needs to be conducted to completely understand the hazard at hand and the impact it might have. The decision tree and the items to investigate provide for a good characterization of the hazard (induced/triggered seismicity) but lack an investigation of the impact (damage). The UIC regulations would limit the damage to a USDW and the document does nothing to define how to investigate and characterize the potential for "damage" (contamination) to a USDW. a. Pg ES-3, prgh 2, ln 7-9: I agree with the statement but would add the need for a risk management phase of any investigation. See above.

BY ROBIN MCGUIRE, CONSULTANT

Class	**Robin McGuire** *Consultant*
Review (see Main body)	**5.6 Errors in Scientific Descriptions** 1. The section labeled "Geologic Stress Considerations," page 6, says that "…a principle (sic) stress direction exists…" and goes on to talk about the orientation of faults with respect to the "…the principal stress direction." This section is an erroneous condensation of parts of Appendix M, which describes "…three principal stresses that are oriented perpendicular to one another." In fact it is the orientation of faults with respect to the orientation of the three principal stresses that is important. This concept is not accurately stated on page 6.
Review	2. Seismologists do not write about "low magnitude earthquakes…" (see page ES-1 and elsewhere throughout the Report). "Low" is a descriptor of elevation, altitude, or level, not size. The correct description is "small magnitude earthquake."
Review	3. The term "fault of concern" is used repeatedly (see footnote, page 2, and Glossary), and is defined as "a fault optimally oriented for movement …" Faults do not have to be optimally oriented with respect to the stress field, to generate an earthquake. For an example, see Appendix E, "North Texas Area Lessons Learned," page E-19, bullet 1, where optimal orientation is described as north-south, but regional faults are predominantly oriented northeast to southwest. I would change the definition to "a fault oriented conducive to movement …"

BY CRAIG NICHOLSON, ACADEMIA

Class	**Craig Nicholson** *Academia*
Review	5.2 Previous Studies (first few) In several places the report makes the statement "Evaluation of induced seismicity is not new to the UIC program" (e.g., page ES-2, par. 1). This statement is certainly true but it should be properly documented, and expanded to acknowledge the earlier reports specifically prepared for EPA that discuss this topic of injection induced seismicity and introduced criteria the UIC Director may use to help minimize and manage the potential of induced seismicity related to deep injection well activities [Wesson and Nicholson, 1987; Nicholson and Wesson, 1990]. The reference for Nicholson and Wesson [1990] is briefly mentioned in the report, but not as a report specifically to EPA that also provides the first set of criteria for minimizing the potential for injection induced seismicity. In fact, the complete, correct citation for these two publications are: • Wesson, R.L. and C. Nicholson, Earthquake hazard associated with deep well injection: A report to the U.S. Environmental Protection Agency, U.S. Geological Survey Open-file Report 87-331, 108 pp. (1987). • Nicholson, C. and R.L. Wesson, Earthquake Hazard Associated With Deep Well Injection—A Report to the U.S. Environmental Protection Agency, U.S. Geological Survey Bulletin 1951, 74 pp. plus plate (1990).
Review	A possible solution to properly acknowledge this previous work that bears directly on the purpose and intent this report is to expand the sentence (page ES-2, par. 1) to say something like: Evaluation of induced seismicity is not new to the UIC program and in fact, over 25 years ago, EPA Office of Drinking Water commissioned a study by the USGS on the earthquake hazard associated with deep well injection [Wesson and Nicholson, 1987; Nicholson and Wesson, 1990]. This previous work established the first set of criteria for site selection, well drilling and completion, as well as for well operation and monitoring to help minimize and manage the potential for injection induced seismicity. Many of these same criteria and practical approaches are also utilized in this newer, updated UIC report.

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
No response	1. The UIC-NTW is commended for clearly stating in the Executive Summary that "EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity" and "of the approximately 30,000 Class II disposal wells in the U.S., very few (<10) disposal well sites have produced seismic events with magnitudes greater than M4.0". This is an extremely important point to make in informing the public, stakeholders, and regulatory bodies with clear information that in the decades of operations, and tens of thousands of wells, there is not a single documented instance of groundwater contamination associated with Class II disposal wells considering induced seismicity.
No Response	2. Page ES-2, Executive Summary Suggest revising the sentence "(1) pressure buildup from disposal activities, (2) faults of concern, and (3) a pathway for the increased pressure to communicate with the fault" to provide more precise definition of terms as discussed in the response to charge questions; and consolidate the listing of definitions of enhanced clarity.
Review	3. Page ES-3, Executive Summary Suggest restating the sentence "with useful practical tools for managing and minimizing injection-induced seismicity are recommended" to "…managing and minimizing significant injection induced seismicity" to align with the report recommendation that hazards are from faults of concern and significant injection induced seismicity. Non-hazardous levels of seismicity (or micro-seismicity) may be present.

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Review	There are probably more than 10 wells in the United States that fall into the "suspect" category, especially since less clear-cut cases often have several well nearby that could be the cause of recent seismicity.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Review	1. P. ES-2 The statement "A basic assumption is that an accurate history of seismic monitoring in the region of the injection well exists" is at variance with other statements in the text. This statement should be qualified to note that the accuracy of such monitoring depends on the robustness of the seismic network for any given area and with consideration for how long such a network has been in place. As is well stated elsewhere in the document, both epicenter and hypocenter location determinations will be dependent upon the number of monitoring locations.
Review	2. P. ES-3 It is recommended that the last sentence on this page be modified to include hydrogeology, seismology, petrophysics, and geomechanics as part of a multidisciplinary approach.

COMMENTS ON MAIN REPORT

BY JEFF BULL, OIL/GAS INDUSTRY

Class	**Jeff Bull** *Oil/Gas Industry*
Clarify	1. Pg 1, prgh 3, ln 5-6: I agree that disposal wells have a greater potential for pressure buildup but nowhere in this document to you state that pore pressure dissipates as you move away from the well (pore pressure diffusion). Yes, over a period of time, the length of which is dependent upon the hydrogeologic characteristics of the formation into which one is injecting, the pressure in the area might build up but it still will be the highest at the point of injection and then dissipate as it radiates out into the vastness of the surrounding formation.
No Response	2. Pg 2, prgh 2, ln 8-9: The size of the footprint is highly variable depending upon the hydrogeologic characteristics of the formation. See comment 3 above. The higher the pressure at the well head does not always mean the farther the footprint will reach out away from the point of injection. The pressure is higher because the porosity/permeability restricts the flow of water and so the water and its associated pore pressure may not travel as far. Likewise the opposite is true in that low pressure at the bore hole means the formation is receptive to water flow and so the pressure footprint, albeit lower, may reach out farther from the point of injection.
Review	3. Pg 2, prgh 3, ln 7: I agree with the statement but more specifically, hydraulic fracturing has the potential to create felt events at the surface when the stage being fractured transects a fault such as what occurred during the Horn Valley, BC, Cuadrilla, UK, or recent eastern Ohio events. a. Note that in footnote 12 called out in the line referenced above, you have definition of a fault of concern. This definition is different than the one listed on Pg ES-2, footnote 5. The footnote 12 definition is more complete and should be used throughout the report.

Class	**Jeff Bull** *Oil/Gas Industry*
Grouped-Scope & Authority	4. Pg 3, prgh 3, ln 1-4 I agree with this approach because there is way too much we don't know about the topic of induced/triggered seismicity so there is no black and white approach to regulating it; it has to be on a case by case basis with a fit for purpose evaluation. As indicated in other comments, I believe the decision tree is lacking a risk management evaluation which would provide the best input as to how exhaustive/intense the evaluations should be that are undertaken in accordance Director discretionary authority. As an example, the seismicity detected in Horn Valley, BC had little impact at all because few structures were located in the immediate area and the impacted population was for the most part non-existent. In comparison the seismicity detected in populated areas needs to be investigated more thoroughly as the impact would be greater. At the same time, I would be remiss to not point at again that the UIC jurisdictional authority is for protection of USDW and not protection of property.
Grouped-Authority	5. Pg 3, prgh 4, ln 1-4 This document is lacking any definition of, or characterization of the threat of induced seismicity to USDW and has no elements in the decision tree to define the threat. See comment 2 above.
No Response	6. Pg 6, prgh 3, ln 2-5: I agree with the statement but would add the context that the buildup of tectonic forces (insitu stress) takes place of years and that when the buildup is sufficient to cause a slip, there is a release of the energy and then the buildup process starts all over again. As a result, there can periods of quiet with no or limited seismicity and then active periods of seismicity followed by periods of quiet; and the cycle repeats itself.
No Response	7. Pg 6, prgh 3, ln 8-10: I agree that the tectonic geologic stresses may be transferred over great distances, but the pore pressure that could trigger a seismic event is relatively localized depending on the hydrologic and geomechanical characteristics of the formation.
No Response	8. Pg 7, prgh 3, ln 1-2 & 6-7: See comment 4 above. The presence of horizontal and vertical error ellipses by itself indicates that the topic at hand is not an exact science and as such requires a risk management approach.

Class	**Jeff Bull** *Oil/Gas Industry*
Clarify	9. Pg 8, prgh 2, ln 8-9: The discussion in this line, and in others in the document refereeing to fracture flow, implies that the formation into which you are injecting has been fractured (creation of cracks or faults in hard rock). This is not always the case and is not the predominant formation type into which water is disposed. Rather the disposal formation is typically a porous sedimentary formation that, through its formation, has interstitial space created by varying particle size and shape, that when packed together creates flow channels.
Clarify	10. Pg 8, prgh 4, ln 5-7: The statement is not accurate. Petroleum engineering methods focus on an existing pressure within a vast area (40-160 acres based upon allowable well spacing) that "pushes" the product (gas or liquid) into a well and as product is removed the pressure will dissipate over time. An injection well operates in the reverse with the highest pressure at the well that dissipates as the pore pressure radiates out form the well. See Basic Mechanism of Injection Induced Seismicity – comments 3 and 4.
Clarify	11. Pg 8, prgh 4, ln 10-12: The statement is not totally accurate as it is the pore pressure that radiates out from a well that interacts with the well. Yes there is a potential that the liquid may reach a fault but the liquid does not grease the existing fault and cause it to slip. The pore pressure disrupts the insitu stress field that is holding the fault together and causes it to slip. a. The statement regarding "unknown distance" is critical when considering how far the pore pressure will travel. And as it travels, the pore pressure is dissipated, so knowing the distance and perturbation of pore pressure is important. Note that understanding the perturbation of the pore pressure requires very specific data that is rarely known and has to be estimated and sophisticated modeling that is very expensive ($50-150,000/well)
No Response	12. Pg 9, prgh 2, ln 1: The statement that the "review of operational data can provide a qualitative look at the well behavior" is accurate. However the key word in the statement is qualitative. The use of qualitative implies a degree of uncertainty that requires the use of a risk management protocol to provide context to the review.

Class	**Jeff Bull** *Oil/Gas Industry*
Review	13. Pg 10, prgh 1, ln 2-3: You need to define the term "static pressure". In petroleum reservoir terms, static pressure is the natural pressure within the formation (i.e. formation pressure). The injection pressure is the pressure it takes to push the fluid down the bore hole and out into the formation. A comparison of static pressure to injection pressure is representative of the pore pressure at the bore hole that then radiates out from the bore hole and dissipates with distance. During normal operation of a disposal, should the injection pump be turned off, the injection pressure would bleed off over time back down to the static or formation pressure. The rate of the bleed off is based upon the hydrogeological characteristics of the formation into which one is injecting.
No Response	14. Pg 10, prgh 3: Need to add the respective state geologic survey (i.e. Oklahoma Geologic Survey) as a reference for local state information and data. The state survey offices are focused on the specifics of their state where as the USGS has a national/world view.
No Response	15. Pg 12, prgh 4, bullet 1: The geographic association between the injection zone and the location of the earthquake is important and needs to be accurate. However the accuracy is difficult as mentioned in comment 4 above. It must also be understood that a spatial and temporal determination (geographic and time association) is not sufficient to define causation. As mentioned in several places in this report, causation requires a multidisciplinary approach. And even then a risk management evaluation should be done because a multidisciplinary approach will typically not come up with a definitive cause for what has occurred (existing wells) or what might occur (new wells).
Clarify	16. Pg 12, prgh 4, bullet 2: The statement regarding exceedance of the theoretical friction threshold implies that the injection water lubricates the surfaces between the 2 sides of the fault allowing one side to slip along the other side. As presented in Basic Mechanism of Injection Induced Seismicity – comment 1, the primary mechanism is the disruption of the insitu stresses holding the fault together by pore pressure radiating our from the point of injection.

Class	**Jeff Bull** *Oil/Gas Industry*
No Response	17. Pg 12-13, prgh 5 and associated bullets: the classic Davis and Frohlich "7 questions" only evaluate the hazard (seismicity). You need to add an evaluation of the impact and then conduct a risk management analysis considering both the hazard and the impact.
Group-Scope	18. Pg 20, prgh 3, sub bullet: Note that the immediate and permanent shut down of suspect wells, does not allow one to conduct a thorough investigation; including conduct of injection step test, pressure fall off, and seismic activity versus injection pressure and flow rate. All of which are important to define a potential management protocol to minimize the impact of potentially induced seismicity related to the suspect well, which is the objective of this document
No Response	19. Pg 21, prgh 1, sub bullet: 3D seismic data is proprietary data and, depending upon the owner and/or the licensing terms between the owner and the user, the data may or may not be able to be shared.
Group-Scope	20. Pg 24, prgh 3, ln 1-4: When identifying "a concern", one should identify some impact specific criteria because what may be a concern in and around the Dallas/Fort Worth area may not be a concern in Enid, OK or in the Oklahoma/Texas panhandle based solely on the wide range of demographics (population density, types of structures, construction methodology. The definition of the criteria should be based upon a risk management evaluation.
Group-Scope	21. Pg 25 Decision Model: The decision model is very similar to the one developed by the AXPC SME group as well as having many common elements that are being discussed in OK, TX, and KS. The aspect that is missing is that in providing answers to some of the questions asked, one will typically not have a definitive answer. This is because the science of induced seismicity and even natural seismicity has not been perfected. In review of the case histories, it should be noted that the primary piece of evidence used to shut the wells down was spatial and temporal correlations which does not define causation. For this reason, a risk management evaluation should be added. See other comments regarding the use of a risk management approach.

Class	**Jeff Bull** *Oil/Gas Industry*
No Response	22. Pg 26, prgh 2, ln 3-4: The establishment of a maximum injection pressure is already done during permit and is typically based upon operating the injection well at a pressure below the pressure required to fracture the formation in which the well is injecting. Also, in most case there is a built in safety factor by specifying a specific % below the pressure required to fracture the formation.
Grouped-Scope	23. Pg 26, prgh 4, ln 4-6: The multidisciplinary approach needs to include civil engineers to defining the shaking or movement that that takes place at the surface because that is the impact. This involves the use of shake maps and the Mercalli scale which defines intensity of the seismic activity using peak acceleration or peak velocity at the epicenter (surface) where the seismometer is located. a. By using the Mercalli (or Modified Mercalli) scale you can define the potential for damage by comparing the peak acceleration/velocity to the building codes or construction techniques for the structures in the area. This should be part of the overall impact analysis undertaken as part of the risk management evaluation.

BY ROBIN MCGUIRE, CONSULTANT

Class	**Robin McGuire** *Consultant*
Review	**Errors in Scientific Descriptions** 1. The section labeled "Geologic Stress Considerations," page 6, says that "…a principle (sic) stress direction exists…" and goes on to talk about the orientation of faults with respect to the "…the principal stress direction." This section is an erroneous condensation of parts of Appendix M, which describes "…three principal stresses that are oriented perpendicular to one another." In fact it is the orientation of faults with respect to the orientation of the three principal stresses that is important. This concept is not accurately stated on page 6.

Class	**Robin McGuire** *Consultant*
No Response	2. Three key components necessary for IS are described repeatedly throughout the Report (see page 8). The 3rd is "a pathway for increased pressure to communicate with the fault of concern." This leaves the impression that Induced seismicity occurs because injected fluids travel along pathways and lubricate faults, which is incorrect. Induced seismicity occurs because pore pressure changes in the earth's crust change the amplitudes of one (or more) of the 3 principal crustal stresses, causing increased shear stress across the fault surface, resulting in fault slip. A more accurate statement of the 3rd key component would be "a pathway for increased pressure to communicate with the earth's crust in the vicinity of a fault of concern." a. Another detail is that the terms "pore pressure" and "fluid disposal operations" should be used consistently throughout the Report, to emphasize that fluids play a critical role.
Review	3. It's unclear what group actually wrote this Report. Page 3 defines the NTW (National Technical Workgroup of EPA) and the WG (the Induced Seismicity Working Group, some of whom are outside of EPA), and the WG members are listed on page 31. The Executive Summary indicates that the NTW is taking credit for the Report, but page 5 has sections titled "Working Group Tasks" and "Working Group Approach" that gives the WG strategy to develop the Report. The WG and/or the NTW should determine how to handle this administratively.
Clarify	4. The Report goes into depth on describing petroleum engineering characterizations (fluid flow, effects of strata permeability and continuity on well performance), seismology (earthquakes and seismic monitoring), and injection operations (decisions on fluid pressures, volumes, and tests) but fails to pull that knowledge together into concrete technical recommendations for "minimizing and managing potential impacts" of IS (per the Report title). The Executive Summary, page ES-2, states "This report is not a guidance document and does not provide specific procedures, but does provide the UIC Director with considerations for addressing induced seismicity on a site specific basis…" This appears to be a failed opportunity to recommend some specific technical steps that could be taken to "minimize and manage potential impacts." The reason stated in the Report for this generality (page 26) is "The site assessment considerations are intended to guide the Director in selecting operational, monitoring, and management approaches that are appropriate to address induced seismicity issues." I expected the Report to recommend such approaches. If specific technical recommendations cannot be given or are not appropriate (e.g. because of the many variables that can affect induced seismicity at individual sites), the reasons should be stated.

Class	**Robin McGuire** *Consultant*
Clarify	5. (Report page 8). Because reservoir engineering analysis methods use data from one location (the well), they cannot identify flow patterns or directions, and hence cannot determine if injected fluid is traveling toward or away from an identified "fault of concern."
No Response	6. (Report page 8). Seismologic data (earthquake locations from a seismograph network) can identify the time, location, and size of earthquakes, and these can be correlated to well operations (injection pressures, volumes, etc.). The classic analysis of this type identified IS caused by deep fluid disposal at the Rocky Mountain Arsenal. a. Without a combined approach (petroleum engineering methods, plus earthquake location data, plus at least a general picture of crustal geology), efforts to understand IS and its connection with a particular injection site will be unsuccessful. This point is not stressed enough in the Report.
Review	7. The entire Report needs a detailed scrubbing by a technical editor. There are problems in verbiage, consistency, and grammar on every page, to the extent that this version should be considered a "rough draft." (not inc. here)
Grouped-Scope	**5.5 Completeness of Recommendations** 8. As discussed above in #6, the recommendations given in the Report are more general than specific, and are called "considerations" (see the quote in #6 above) rather than "guidelines" or "technical recommendations." I was expecting to see recommendations such as the following: "The occurrence of multiple magnitude 2.5 or greater earthquakes within 5 km of a well should trigger one or more of the following actions: (a) requiring hourly monitoring and reporting of injection well pressures and fluid volumes, (b) requiring step rate tests or falloff tests of the injection well, and (c) requiring a seismic monitoring array to be set up that could record earthquakes magnitudes down to 1.0 within 10 km of a well." If specific technical recommendations cannot be given or are not appropriate (e.g. because of the many variables that can affect induced seismicity at different sites), the reasons should be stated.
Review	9. The "Technical Recommendations…" document in Appendix A says that output of the study should include "Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations." Such a comparison is missing (unless I overlooked it).

Class	**Robin McGuire** *Consultant*
Review/ Clarify	10. The "Technical Recommendations…" document in Appendix A says that output of the study should include "Recommended measurement or monitoring techniques for higher risk areas." These measurement or monitoring techniques are described in general terms such as injection well operational characteristics, or seismic monitoring arrays, for any well where induced seismicity is a concern. No special recommendations are given for "higher risk areas."
Review	11. The "Decision Model" section of the Report (page 22+) says that the decision model addresses 3 scenarios involving disposal wells and seismicity. However, it does not mention an important case: a new disposal well that is proposed in a region that is experiencing seismicity, possibly related to existing wells. Does the decision model cover that case? If not, how should the Director make a decision for such a proposed well?
Review	12. The "Research Needs" section uses the following terms in 3 paragraphs (page 27): ▪ Injection well operating data ▪ Operating well behavior ▪ Injection well operational characteristics ▪ Disposal well operational behavior ▪ Disposal wells operating parameters Do these terms mean the same thing, or are there subtle, unexplained differences? The reader is left muddled.
Review (see Appendix D for equation)	13. The section titled "Petroleum Engineering Applications…" (page 8) introduces the phrase "Hall integral and derivative responses" but does not explain what this is. Appendix D, "Petroleum Engineering Considerations," explains the Hall integral (page D-9) as "…a numerical integration between the operating BHP and static (reservoir) BHP." Why is an equation not given? Bullets on pages D-9 and D-10 indicate the Hall integral is the "cumulative ($\Delta P*\Delta T$) function" and the Hall integral derivative as the "difference between successive Hall integral values," divided by the "difference between successive cumulative injection values." Yet if I look at Figure D-4 showing the "Hall integral with derivative", applying the above definitions, I calculate an average derivative value of 0.12, not values of zero to 60,000 as shown on the plot. Obviously I am missing something, and other readers will be muddled as well.

BY CRAIG NICHOLSON, ACADEMIA

Class	**Craig Nicholson** *Academia*
Review	1. I have other minor corrections or comments on the report text, which I can send as an annotated pdf copy with comments as inserted pdf sticky notes. An annotated copy is available in the Peer Review Record.
Review one/ No response others	2. My concerns about the report generally fall into 3 categories: 1) incomplete or inadequate acknowledgment of previous studies and EPA reports on this very topic that provide similar recommendations, criteria or practical approaches to help minimize the potential of injection induced seismicity; 2) a lack of discussion on the importance of total volumes of fluid injected as a contributing factor to the potential for and maximum magnitude of injection induced seismicity; and 3) to some extent, an underlying assumption that the only faults of concern for injection induced seismicity are faults of sufficient length that are "optimally oriented for movement and located in a critically stressed region".
Clarify	a. Another important factor contributing to injection induced seismicity, besides the pore pressure increase from disposal operations, a stressed fault and a pathway for communication of the pressure increase, is the actual volume of fluid injected. For example, as previously mentioned, high fluid pressures can hydraulic fracture intact rock and at the same time induce small earthquakes. However, even if the fluid pressures used in hydraulic fracturing are high, if the volume is small, the resulting induced events are also typically small. Only if the volumes of fluid injected also become large does it appear that the potential for inducing large magnitude earthquakes also increases [McGarr, 2014].
No Response	b. …… In summary, although the three components listed due contribute to injection induced seismicity, other elements such as the state of stress, the proximity of the stressed fault to the well, the amount of pore pressure increase and the volume of fluid injected by disposal operations can also play a significant role.

Class	**Craig Nicholson** *Academia*
Clarify	4. Again, improving the quantity, quality, and timeliness of information on injection volumes and pressures reported to regulatory agencies along with increased seismic monitoring for small earthquakes (M1.0 or less) is often much more important to managing the earthquake risk from injection activities, or minimizing the potential for injection induced seismicity, than performing additional reservoir engineering analyses with what in some cases is less-than-ideal or insufficient data. a. The primary goal is to evaluate the pressure-time histories or pressure buildup associated with volumes of fluid injected to better understand reservoir characteristics and the extent to which assumptions, such as a homogeneous reservoir with radial flow, are appropriate. b. Most multidisciplinary studies of injection induced seismicity already perform these basic types of reservoir analyses. Any deviation from radial flow, or any indication of increased transmissivity should be scrutinized as possible evidence for increased flow towards and pressure buildup at potentially adjacent faults, or as possible evidence for the opening of fractures or the occurrence of new faulting. c. Conducting more sophisticated reservoir engineering analyses besides these basic reservoir modeling studies can in some cases provide additional insight into reservoir behavior and its response to fluid injection, but without adequate input data, such studies often prove to be ambiguous.

Class	**Craig Nicholson** *Academia*
Review	**5.2 Previous Studies (last)** 5. Other more up-to-date references are listed under Charge Question 4 that would also be useful to incorporate. I also found it somewhat misleading to make statements like: "The review of injection-induced seismicity literature revealed a lack of a multidisciplinary approach inclusive of petroleum engineering techniques" (page 8, 2nd para). a) Several studies on injection induced seismicity are quite multidisciplinary, and although they may not use the entire suite of reservoir engineering techniques proposed in this report, they do investigate injection pressure-time histories and volumes, reservoir characteristics, subsurface geology defined by exploratory test wells, inferred pore pressure changes at a distance from disposal operations, historical and recent seismicity and even the pressure fluctuation response in shallow wells as a result of adjacent seismic activity [e.g, Nicholson et al., Bull. Seismo. Soc. Am., 1988]. Many of these techniques are also used by the petroleum industry to characterize the hydrogeologic response of reservoirs.
Clarify	5.3 Injection Induced-Seismicity Contributing Factors 6. Although it is indeed true that most existing models used to explain the fundamental mechanism of injection induced seismicity focus on the net pore pressure increase associated with disposal operations, another key contributing factor to the potential for induced seismicity is the volume of fluid injected. This factor also seems to strongly influence the maximum magnitude of the induced earthquake [McGarr, 2014]. The reason for this correlation may be that increasing volumes of fluid allow the pressure effects from well operations to extend farther from the injection well and thus increase the potential that the pressure front will encounter more and larger stressed faults that are close to failure, or that the increased volume allows a larger section of a stressed fault to be brought closer to failure, resulting in a larger earthquake once rupture initiates. Regardless, in providing practical approaches to manage and minimize the potential for injection induced seismicity, it would seem prudent, based on a number of case histories, that the volume of fluid injected, as well as injection pressures and changes in transmissivity also be consider an important factor.

Class	**Craig Nicholson** *Academia*
Group-Scope	5.4 Injection Induced-Seismicity Faults of Concern 7. The authors are correct in that it is typically true that a major contributing factor to most injection seismicity is the presence of a stressed fault whose failure was triggered by the increased pore fluid pressure associated with the disposal operations. In the report though, there is an underlying presumption though that this stressed fault is favorably or optimally oriented for slip in the current tectonic stress field. However, this assumption is only true if it is the minimum increase in pore fluid pressure that triggers slip or motion on the fault. Higher fluid pressures can induce slip on less favorably oriented faults. Certainly if fluid pressures are high enough to hydraulically fracture intact rock, it is also capable of triggering slip on less favorably oriented existing faults or zones of weakness. The point is that although optimally oriented faults within the current tectonic stress field would indeed be most likely to fail with any increase in pore fluid pressure, other faults can and have failed as a result of injection operations. Keeping downhole injection pressures below the threshold to trigger slip on favorably oriented faults would help minimize the potential for injection induced seismicity. Unfortunately, the report does no really discuss how to determine what this threshold might be, even though procedures for estimating this threshold based on the Mohr-Coulomb failure criteria are widely discussed in the literature.

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
Review	1. In performing my peer review, I considered the charge questions and the project framing around 6 key objectives (as described on page 5 of the report): • Identifying the parameters that are most relevant to screen for injection-induced seismicity; • Identifying siting, operating, or other technical parameters that are collected under current regulations; • Identifying measurement tools or databases that are available that may screen existing or proposed Class II disposal well sites for possible injection-induced seismic activity; • Identifying other information that would be useful for enhancing a decision making model; • Identifying screening or monitoring approaches which are considered the most practical and feasible for evaluating significant injection-induced seismicity; and • Identifying lessons that have been learned from evaluating case histories. Based on the information as summarized in the main body and appendices of the report, Objectives (2) and (6) appear to have been addressed. However, Objectives (1), (3), (4), and (5) do not appear to be clearly and/or effectively addressed in the report. … Adding a section that clearly provides specific summary "answers" to each of the six "project objectives questions" would substantially improve clarity of communication. Alternatively, the "Report Findings" section on page 30 could be revised to specifically address each of the project objective questions.

Class	**Kris Nygaard** *Oil/Gas Industry*
Group-Scope	2. The current draft report does not provide substantive discussion of risk assessment and management approaches, based on sound engineering principles and earthquake/civil engineering considerations, thus creating a significant gap in providing the UIC regulators the information to identify available public information that would facilitate formulation of regulatory decisions that reasonably consider the risk levels and hazard exposures that may exist. ……
Review (see also p. 35; C-2, 5 and 6)	3. The description of a "fault of concern" is problematic from both a scientific standpoint, as well as clarity of communication in the report. From a scientific standpoint, a measure of earthquake size and energy release is the static (or scalar) seismic moment (Mo). The calculation of this quantity is straightforward in terms of the equation Mo = μ D S, where μ is the shear modulus, D is the average displacement along the fault, and S is the surface area of the fault; hence fault length is only one piece of the overall factors defining the energy release. Secondly, it will be hard for the average reader to efficiently comprehend the current definitions as these are located in different places through-out the report. A single, more precise definition, for "fault of concern" could be provided by the following definition below, and could be listed in the definition of terms section. a) …. p. 28 of the report considering the key geologic and engineering factors. This section of the report could be strengthened to better emphasize the risk is associated with "faults of concern" and not "small faults" or stable faults. This shortcoming could be effectively "A fault of concern is defined, for the purpose of this report, as a fault optimally oriented for movement and located in a critically stressed region, is of sufficient size, and possesses sufficient accumulated stress / strain, such that fault slip and movement has the potential to cause a significant earthquake (where a significant earthquake is defined for this report as of such magnitude to potentially cause damage or endanger underground sources of drinking water)"

Class	**Kris Nygaard** *Oil/Gas Industry*
No Response	4. Page 5, Working Group Tasks The sentence "Recommendations for measurements or monitoring techniques for higher risk areas" mentions higher risk areas. With the feedback provided in response to the charge questions, the report should be updated to provide discussion of potential approaches for performing a risk assessment and the attributes of a higher risk area; and then this section should identify or comment on where in the report approaches for risk assessment are discussed.
Review	6. Suggest revising the sentence "(1) pressure buildup from disposal activities, (2) faults of concern, and (3) a pathway for the increased pressure to communicate with the fault" to provide more precise definition of terms as discussed in the response to charge questions. (1) the presence of a fault of concern(a); (2) a subsurface pathway for hydraulic communication from the disposal well to the fault of concern; and (3) a sufficient subsurface stress perturbation primarily induced by the disposal activities, in sufficiently close proximity to a fault of concern, such that the resulting stress perturbations cause the fault of concern to slip. Footnote: (a) "A fault of concern is defined for the purpose of this report as a fault optimally oriented for movement and located in a critically stressed region, is of sufficient size, and possesses sufficient accumulated stress / strain, such that fault slip and movement has the potential to cause a significant earthquake (where a significant earthquake is defined for this report as of such magnitude to potentially cause damage or endanger underground sources of drinking water)

Class	**Kris Nygaard** *Oil/Gas Industry*
Clarify	7. Page 8, Petroleum Engineering Applications for Evaluating Induced Seismicity a. The section "Possible Causes of Induced Seismicity" (p. 10) could be readily edited to provide broad overview of other factors that may be present in combination with disposal operations. The report would be strengthened by clearly summarizing the range of factors the UIC regulators may wish to explore if unexpected seismicity is encountered in a specific area. Such a listing could be done in brief summary form, and highlight the important natural and anthropogenic triggers that can perturb the subsurface stress regimes in proximity to faults. These include: b. Identification of the natural tectonic stress / strain dynamic behavior in area of concern c. Identification/location of natural (dynamic) sources that could lead to subsurface stress perturbations; including naturally-occurring "overburden" formation density changes under drought or excessive rainfall conditions d. Identification/location of natural geothermal "hot-spots" in the area of concern. etc. e. Identification/location of anthropogenic sources that could lead to subsurface stress perturbations (injection wells; production wells; mining / blasting operations, geothermal operations, reservoir impoundment / dam construction, etc.) f. Identification / location of potential synergies between natural and dynamic sources, for example, such as aquifer / groundwater withdrawals for irrigation and human consumption purposes, in combination with drought conditions
No Response	8. The wording "pressure buildup from disposal activities" is problematic from a scientific standpoint; the precise issue, and triggering mechanism is related to magnitude and location of stress perturbations considering the specific perturbation from the disposal activities. A more precise definition to replace the somewhat vague definition of pressure build-up would be to restate this as: "a sufficient subsurface stress perturbation primarily associated with pressure build-up from the disposal operations, in sufficiently close proximity to a fault of concern, such that the resulting stress perturbations cause the fault of concern to slip".

Class	**Kris Nygaard** *Oil/Gas Industry*
Review	9. Page 13, Determination of Injection Induced Seismicity Suggest revising the sentence "Although these approaches are qualitative and do not result in proof of injection-induced seismicity, they may be useful to UIC regulators. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for taking early prudent action to address the possibility of induced seismicity." to further clarify the limits for use of temporal and spatial correlation. The sentence would be better restated as "Although these approaches are qualitative and do not result in positive proof of injection-induced seismicity, they may be useful to UIC regulators as preliminary screening tools to identify the possibility of injection induced seismicity. Evaluating causality requires evaluation of all important natural and anthropogenic triggers that can perturb the subsurface stress regimes in proximity to faults in the local area. As such, proof of induced seismicity is difficult to achieve and may be time-consuming, but is not a prerequisite for taking early prudent action to address the possibility of injection induced seismicity."
Review/Clarify	10. Page 15, N. Texas Area Suggest revising the sentence "Since the two wells were shut-in the frequency of seismic events in the immediate focus area has substantially decreased" as this is contradictory to information contained in the Janská, E., Eisner, L. 2012 publication that that suggests seismicity continued for an extended time period in proximity to one well after shut-in (when considering the DFW airport measurements). Reference available online at the link: Janská, E., Eisner, L. (2012): Ongoing seismicity in the Dallas-Fort Worth area, The Leading Edge, 31 (12), 1462–1468.

Class	**Kris Nygaard** *Oil/Gas Industry*
Review	11. Page 21, Lessons Learned Suggest revising the sentence "Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events" to avoid appearance of making policy recommendations in this section. The lesson learned is better restated as "In the case studies, regional monitoring was insufficient to pinpoint active fault locations and detect smaller events; and more sensitive monitoring systems were required to accurately identify the fault".
Review	12.Page 22, Decision Model Suggest revising the sentence "(1) pressure buildup from disposal activities, (2) faults of concern, and (3) a pathway for the increased pressure to communicate with the fault" to provide more precise definition of terms as discussed in the response to charge questions.
Review	13. Page 26, Research Needs Suggest revising the sentence "For example, areas of expertise should include, but may not be limited to structural and stratigraphic geology; rock mechanics; seismology; reservoir characterization; reservoir fluid flow mechanisms; and disposal well construction, completion and performance" to also explicitly state "geomechanics".

Class	**Kris Nygaard** *Oil/Gas Industry*
Review/ Clarify and Grouped-Scope	14.Page 27, Research Needs The discussion related to "Future research is needed to explore the correlation between disposal well operational behavior and earthquake events. The research should consider interaction between offset disposal wells on the operational plot characteristics along with area geology (flow geometry related to karstic vs. fractured carbonate)" is very problematic that this would tend to imply to the reader that simple analytic tools can be used to evaluate correlation between the disposal well operational behavior and earthquake events. From a practical view, this is simply not the case and analytic models can not represent the complex physics of the problem. Understanding correlations between disposal well operational behavior and earthquake events requires coupled geomechanics-reservoir modeling, accounting for subsurface complexity and the natural tectonic environment. If the intent was for research to explore if simple analytic models can be used as a possible proxy for advanced coupled geomechanics-reservoir modeling and better define the limits of the applicability for simple analytic model use, then this could be a viable research objective. This discussion should be reworded to more effectively describe the intended scope and specific research deliverable(s) for this proposed research need.

Class	**Kris Nygaard** *Oil/Gas Industry*
Review	15. Page 29, Management Approach The sentence "Take action earlier to minimize the potential for additional injection-induced seismicity rather than requiring substantial proof of the causal relationship" reads as a recommendation and is not sufficiently descriptive. Further many stakeholders, when reading this statement, will be concerned that this statement provides a recommendation for judgment that is not grounded in reasonable consideration of facts. This sentence could be restated to better reflect actual management approaches as understood from the case studies. A statement that better reflects the case study approaches would be framed around the following: "When surface felt seismic events unexpectedly occur, regulators are immediately called on by the public to quickly respond to identify the "cause" of the felt seismicity and to "take action" to reduce the likelihood of future seismic events. However there is a significant difference in the resources, skills, time, and effort required to locate seismic events versus actually determining causation. Sound science and spatial / temporal correlations should both be considered when responding to public concerns and taking action earlier to minimize the potential for additional injection-induced seismicity (rather than requiring substantial proof of the causal relationship).
Grouped-Scope	**16. Page 30, Management Approach** The sentence "Thresholds could be based on the magnitude or frequency of event" should be revised to reflect that sound science and common earthquake engineering protocols recommend use of ground shaking values, such as Peak Ground Acceleration, Peak Ground Velocity and this is done because the broad science and engineering community clearly understand that magnitude of an event is not an accurate way to characterize the local ground shaking conditions and identify the hazard level. The use of magnitude values may be reasonable when there is a reasonable correlation established for local ground shaking values as a function of event magnitude and location from event hypocenter. This is the basis for stoplight thresholds based on sound science (consider the Geysers example). The sentence should be supplemented to reflect accepted engineering practices - "thresholds based in part on event magnitude should consider appropriate correlation (based on event magnitude and hypocenter location) to local ground shaking metrics such as PGA and/or PGV such that thresholds are triggered before hazardous levels of ground shaking are encountered.

Class	**Kris Nygaard** *Oil/Gas Industry*
No Response	16. Page 30, Report Findings (**excludes 'as said earlier')** a) Suggest revising the sentence "(1) pressure buildup from disposal activities, (2) faults of concern, and (3) a pathway for the increased pressure to communicate with the fault" to provide more precise definition of terms as discussed in the response to charge questions. b) The sentence "research is needed to explore the correlation between disposal well operational behavior and earthquake events" should be reconsidered as discussed above (p. 27 Research Needs comment). This should be revised to provide more specific context and identification of possible research deliverables.
Grouped-Scope: a Review: b-d	17. Page 34, Terms a) The table that describes Magnitude versus Earthquake Effects should be revised or supplemented to include ground shaking characterization and examples for different local regions how magnitude value may be related to ground shaking, by considering PGA, PGV, or Modified Mercalli Scale. This can be accomplished by referencing USGS information readily available: … b) Should include terms definitions for "Hypocenter", "Modified Mercalli Scale". Peak Ground Acceleration, Peak Ground Velocity. c) Revise the definition of "Fault of Concern" based on comments provided in response to charge questions. d) Revise definition of "Magnitude" to clearly state that this characterizes the energy release at the hypocenter, and is not direct measure of ground shaking, as actual ground shaking is a function of energy release, distance from hypocenter, and local geologic/soil conditions.

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Group - Scope	1. I think the key components described above are a good place to start, but there are some inaccuracies here. a) First, the presence of a stressed fault is somewhat misleading, as all faults at depth are under stress, simply from the overburden of the overlying rock. The report makes a distinction that not all faults are optimally oriented to the stress field, and that faults that are outside of optimal orientation are not "faults of concern", but there is still much we do not understand about fault strength that makes this definition a little constricting in my opinion. The optimal fault angle is in general a good guide to whether a fault might slip, but it should only be a guide. Although the remote stress field is often fairly well estimated from focal mechanisms, borehole breakouts, etc., local stresses on a fault may be rotated from the remote stress field, for example by complexity in fault geometry or the presence of other structures (Scholz and Saucier 1993).

Class	**Heather Savage** *Academic Laboratory*
Clarify	b) Second, in order to determine whether a fault is optimally oriented to the stress field, the frictional strength of the fault must be assumed. The main paper on this issue cited in this document (Holland 2013), assumed that faults have a frictional strength of 0.6 (this is never stated clearly, but the Hurd and Zoback (2012) paper that Holland references does assume this). It should be made clear that this, in many cases is a complete assumption. Townend and Zoback (2000) demonstrate that some mid-continent faults have friction values close to 0.6, but this should not be assumed in all cases. Although the coefficient of friction of bare rock surfaces is typically this high, faults often have granular gouge layers (from abrasion) that are rich in clays, and have a coefficient of friction closer to 0.3-0.4. Hurd and Zoback (2012) argue that faults in the midcontinent do not have gouge zones, but at least through my own personal experience in the field, I would say that is not usually the case. The presence of clays and weakening of faults changes the range of angles a fault can be from the maximum stress direction and still slip. For instance, the San Andreas fault is oriented almost 90 degrees from the maximum horizontal stress, meaning that it should essentially be pinned (Zoback et al. 1987). Although this is an extreme example, it highlights the uncertainty involved in assigning “faults of interest” based on orientation of the fault to the remote stress field. To highlight this point, I will mention that Holland (2013) suggests that faults in Oklahoma that are oriented east-west are unlikely to host earthquakes, despite the fact that a M5 earthquake occurred on an east-west striking fault as part of the 2011 Prague sequence (Keranen et al. 2013). Although this earthquake may have been pushed to failure by other nearby faults at orientations that would classify them as “faults of interest”, the complexity of fault interaction suggests that limiting the scope of investigation to faults at a certain angle may be problematic. A full characterization of all faults in the vicinity of a well seems more appropriate.

Class	**Heather Savage** *Academic Laboratory*
Clarify	c) The other consideration that could be addressed more specifically in this document is that absolute stress levels on faults at any time is unknown, so it is never clear what pressures will be the "tipping point" that causes failure. Time-dependent fault processes, specifically time-dependent frictional properties, should be addressed more in the future as well. Although this is an area of active research, this document would be remiss if it did not at least mention that understanding the processes that involve fault failure is ongoing. For instance, fluid pressure pushes faults towards failure through reduction of effective normal stress, but at the same time make the fault more likely to fail in aseismic slip (Das and Zoback, 2011; Scholz 2002). Aseismic slip on faults can trigger seismic slip further away along the same fault, and this kind of more complex interaction may make spatial interpretation of induced seismicity more difficult.
Review	1. Introduction Page 1 There are now earthquakes in Kansas, so this statement should be revised or removed.
Clarify	2. Introduction Page 1 There has been an earthquake in Ohio recently that is strongly suspected to be hydrofracture-related.

Class	**Heather Savage** *Academic Laboratory*
Review / Clarify	5.4 Injection Induced-Seismicity Faults of Concern (cont) 17. Another general concern that I have is that I think there is way too much emphasis in the report about basement faults. Although many seismically active faults occur within basement rocks, this is not a prerequisite. Because fluid pumping generally occurs within sedimentary sequences, which also have many faults, it is reasonable to assume that either seismic or aseismic processes may begin where the fluid pressures are highest in the sedimentary rocks (i.e. nearer to the well). The 2011 Prague, Oklahoma sequence appears to have started within the sedimentary cover, at least a kilometer above the basement. Some aftershock seismicity continued to within ~250 m of one of the disposal wells (Keranen et al. 2013). I think the suggestion in Appendix B that the depth to basement near a well may be considered in terms of choosing an appropriate site is overstated. Furthermore, the report overstates how aseismic the sedimentary strata above the basement may be. As the report points out, carbonates and sandstone behave mostly brittly. Shales do as well (despite what is written in this report), that is why we extract hydrocarbons from shales by inducing fracture. Although it is true that unconsolidated sediments cannot nucleate earthquakes, when sediments are buried several kilometers they lithify and can behave brittly.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
No Response	1. In general, the basic mechanism of injection-induced seismicity has been captured as is the current state of knowledge. However, since all faults are stressed, the text should clarify that a critically-stressed fault is what is important for consideration. Other factors such as changes in poroelastic stresses and changing hydrologic conditions may also play a role in initiating seismic events which should be considered. …..

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Clarify	2. P. 2 Hydraulic Fracturing It should be noted that the events related to hydraulic fracturing in British Columbia occurred in strata that were very close to basement rock and this is not typically the case with most current hydraulic fracturing operations in the US. As such, these events may be an artifact of the geologic conditions found here and are not generally reflective of conditions found in US based operations.
Grouped-Authority	P. 4 Geothermal Injection Wells The text should provide specific information and examples of how seismic events "could" cause any of the adverse conditions to USDWs to occur. There should also be some characterization of the relative risks as it is considered highly unusual for damage to occur as stated in the text. At what level of seismicity would such be considered possible and what evidence is there to support such suppositions?
Clarify	4. P. 5 1. Injection Induced Seismicity Project Objectives It is suggested that the wording of this be changed to – What parameters are most relevant for the assessment of potential injection-induced seismicity? It is believed that this should be considered a risk assessment exercise.
Clarify	5. P. 6 6. Working Group Approach While it is understood that it would be a considerable task, it would have been useful to study disposal wells in area where no seismic activity has occurred to try to define what differences may exist with those areas where such activity has occurred. It should be noted that the Stanford Center for Induced and Triggered Seismicity is working on developing a detailed stress map of Oklahoma that will be useful to future seismicity assessments there.

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Review Group-Scope	6. P. 6 Background It might also be useful to consider such factors as poroelastic stresses and glacial isostatic adjustment in relevant areas. It needs to be recognized that while surface seismic surveys can be helpful, these cannot always locate faults owing to their size and orientation to the seismic survey. There should also be some recognition that the size of a fault may also be an important consideration. Small faults are unlikely to be contributors to strong surface shaking.
No Response	7. P. 7 Geophysical Data Consideration should be given to examining current data from the various state seismic networks as they usually have more monitoring stations than the USGS and can provide better epicenter and hypocenter locations.
No Response	8. P. 10 Earthquake Reporting In addition to the regional seismometer networks measuring activity at lower magnitude thresholds, this is also true to some extent from the Earth Scope Array data and both can create the appearance of increased activity due to improved monitoring capabilities. Nevertheless, this is useful information for evaluating and assessing induced seismicity potential.
No Response	9. P. 12 Possible Causes of Induced Seismicity Noting the presence of alternative causes of seismic activity such as change in lake levels is a useful point. It should also be noted that changes in ground water levels may occur concurrently and contribute to induced seismic events. Other possible causes such as mining or blasting might be noted also.

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Review	10.P. 20 Common Characteristics and Observations a) Third bullet - This statement could be more precise by stating "basement rock faults" rather than just basement rocks. b) Another bullet could also be added about the lack of a sealing layer between the injection zone and the basement faults.
No Response	11. P. 22 Director discretionary authority was used to solve individual site specific concerns. Fourth bullet – While the moratorium imposed in Arkansas represents an abundance of caution and respect for public concern, from a scientific standpoint it would have been useful to continue to allow the operation of the shallower disposal wells to ascertain if the seismicity would subside since they were several thousand feet above basement rock faults
Review	12. P. 22 Decision Model Again, significant changes in ground water levels might also be considered.
No Response	13.P. 25 Injection Induced Seismicity Decision Model It should be noted that it can be difficult to distinguish between natural and induced seismic events. One of the factors to be considered is if there is a sealing barrier between the injection zone and basement rocks.

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
No Response	14.P. 26 Research Needs a) Expertise in hydrogeology, petrophysics and geomechanics should be included in the list for a multidisciplinary approach. b) More research into the role of hydrologic factors is warranted as it is apparent from a review of seismic events over the past couple of years that there are spatial and temporal correlations in some areas with changes in reservoir and ground water levels. Where such changes occur in close proximity to disposal operations, it may be difficult to distinguish between the two as possible causes of events. c) Development of methodologies for improving the identification of critically stressed faults. d) Assess how various depths of injection activities and proximity of injection to basement rock influence potential maximum event magnitudes. e) Determine whether methodologies can be developed for better distinguishing between natural and induced seismic events. f) Assessment of whether natural seismicity can influence the triggering of events related to injection and what factors would be relevant in such an assessment. g) Assessment of how injection rates influence pore pressure diffusion under various subsurface conditions. h) Methods for determining the velocity of pore pressure propagation down a fault. i) Influence of the various types of faults on potential seismic events. It could be that the curvature of faults can be useful in assessing the risk of events.

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
No Response	j) What factors control the decay of seismicity following an event? Determination of what factors control the maximum length of time that induced events could be expected following cessation of operations. k) Identification of seismic sensing technologies that can provide for lower cost and greater sensitivity and additional technological advancement needed to provide more useful and accurate data. l) Development of ground motion prediction models for triggered seismicity. m) Development of more detailed stress maps for areas of concern. This would be an expansion of work already underway in Oklahoma by the Stanford Center for Induced and Triggered Seismicity. n) How do soil conditions and local geology impact wave propagation and amplification? o) Development of better calibrated velocity models. p) Better information on the nature and thickness of sealing formations between injection zones and basement rock and how such may minimize the potential for induced seismic events.
Clarify	15.P. 28 Preliminary Assessment of Existing or New Oil and Gas Waste Disposal Wells Second bullet – It would be useful to suggest over what time frame increases in frequency or magnitude should be reviewed. It is suggested that this should be performed covering a period of at least one year prior to the assessment.
No Response	16. P. 29 Operational Approaches First bullet on page – It would be useful to suggest what frequency should be considered for periodic pressure measurements.

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Review	17. P. 29 Management Approach First bullet – This is a very open-ended statement and leaves its interpretation open to question which can result in the second guessing of Directors later on. It is suggested that this statement could be better clarified.
Clarify	18. P. 30 Management Approach Third bullet – A stop-light approach such as has been suggested by various authors and organizations such as the National Academy of Sciences should be endorsed as a practical tool for regulatory agencies to follow with the particulars left up to the agencies to reflect their particular geology and concerns.
Clarify: a Review: b	19. P. 30 Report Findings a) Fourth bullet – It needs to be recognized that while a petroleum engineering approach can provide useful information, such approaches can be very time consuming and that there are various factors that can impact the accuracy of the outcomes from such. b) Sixth bullet – It is suggested that the wording here be modified to include the word "possible" between the and correlation. As stated, this reads as a definitive case which it is not.
Group-Scope	20. P. 36 Terms It might be useful to define terms for peak ground acceleration and peak particle velocity as these would be of most potential concern to the operational integrity of any surface equipment associated with injection disposal operations. In addition, a discussion around these terms should be included in the appropriate places in the text.

COMMENTS ON APPENDIX B: DECISION MODEL

BY JEFF BULL, OIL/GAS INDUSTRY

Class	**Jeff Bull** *Oil/Gas Industry*
Grouped-Scope	1. Pg B-2, prgh 1, ln 3-4: The key word in this sentence is "possibility". The use of spatial and temporal correlations does not define cause and effect. You need a multidisciplinary approach to attempt to define cause and effect. And even then it will be rare that one can define a definitive cause and effect thus the need for a risk management approach to any evaluation of the potential for injection induced seismicity; pre drilling/operation and while operating.
Clarify	2. Pg B-2, prgh 4, ln 2-4 and prgh 5 ln 2-4: The USGS historical seismicity map along with other regional historical seismicity data is all regional and can help understand regional seismicity but it is not useful when zeroing in on an injection well location whose area of potential impact smaller than the error ellipses for historic seismic events that could led to a false positive determination
Clarify	3. Pg B-3, Existing versus new wells general: In general, available data outlined on page B-4 is not available for existing wells as a lot of the geologic, hydrologic and geosciences data can only be obtained when the well is drilled or completed. In addition, most existing wells will not have seismic data to locate faults in area and if it is available it will most likely be 2D seismic which has poor resolution and rarely 3D seismic data. If the 3D seismic data is available, the 3D seismic data might not be deep enough to map the basement faults because the target of the 3D seismic data is the hydrocarbon producing zone which is typically above the injection zone.
No Response (see p. B-3)	4. Pg B-3, prgh 5, ln 3-4: The proximity of existing wells (and adding new wells) within an area and in the same formation of other injection wells, needs to be considered in an effort to not have a concentration of pore pressure in an area versus spreading it out over a larger area
Review	5. Pg B-3, prgh 5, ln 7-9: The proximity to the basement is not as critical as proximity to a critically stressed, favorably oriented fault. (See Basic Mechanism of Injection Induced Seismicity – comment 2). If there is no fault in area or no critically stressed favorably oriented fault in the basement area, one can successfully operate an injection well injecting into or near the basement

COMMENTS ON APPENDIX C: GEOSCIENCE

BY JEFF BULL, OIL/GAS INDUSTRY

Class	**Jeff Bull** *Oil/Gas Industry*
Group-Scope	1. Pg C-9, prgh 2-4: There is a discussion of Mercalli/Modified Mercalli in Appendix C but then it is ignored in the development of the decision tree. The document lacks a discussion as to how it can be used in evaluating potential damage from induced/triggered seismicity. Any discussion of damage has to include the discussion of the mechanics as to what could cause the damage. Yes the seismic event propagates the waves of energy that travel through the earth, but it is the resultant shaking that causes damage. The document presents the traveling of the released energy as it relates to locating the hypocenter, but it does not discuss the dissipation of the energy released as it radiates out from the hypocenter towards the epicenter. It is the amount of energy at the epicenter and surrounding area that chases shaking resulting in damage.

BY ROBIN MCGUIRE, CONSULTANT

Class	**Robin McGuire** *Consultant*
Review	5.6 Errors in Scientific Descriptions (continued) 1. The "Seismic Risk" section of Appendix C says the following: "Seismic surface waves are the most likely to be felt, having the greatest amplitude and a motion similar to ocean waves. For the most damaging earthquakes, the earth moves very similar to the surface of the ocean in a storm." This is only true at large distances (>50 km) from the causative fault. Near the fault, body waves have larger amplitudes, are more likely to be felt, and are more damaging. I would remove the focus on surface waves.

Class	**Robin McGuire** *Consultant*
Clarify/Review	**5.7 Unclear Descriptions** 1. The "Basic Seismology" section of Appendix C (page C-5) says the following: "An earthquake (seismic event) occurs when there is brittle failure along a fault at depth. The resulting brittle failure of the fault results in slip or displacement that generates elastic waves that propagate away from the fault. The event can be from a source in, on, or above ground that creates a wave motion in the earth." a) It appears that the discussion is mixing up seismic waves generated by earthquakes, with man-made seismic waves used to create images of what lies underground. As such, the description of earthquakes and seismic waves is muddled. b) Earthquakes generally occur on pre-existing faults, and there is no brittle failure of intact rock. (An exception is during hydraulic fracturing, which is designed to fracture intact rock.) Thus brittle failure does not cause fault slip; fault slip causes strain energy to be released in the form of seismic waves. If "brittle failure" is used as a synonym for fault slip, that is not standard in seismology, and is not consistent with the above quote, which says that one causes the other.

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
Group-Scope	1. Page C-8 to C-10, Seismic Risk: Appendix C should be appropriately revised to address the General Comments (Section I of Peer Review) and in response to Charge Question No. 1. It is very problematic that only 1-1/2 pages are provided in this section on "Seismic Risk", and there is significant omission that several published methods for evaluating injection-related risk of induced seismicity are not summarized in this section. With this significant omission, the NTW report does not appear to have effectively met at least two of the stated project objectives on p. 5 of the report: "what other information would be useful for enhancing a decision making model"; and "what screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection-induced seismicity"

Class	**Kris Nygaard** *Oil/Gas Industry*
Group-Scope	2. The discussion of the May 2, 1983, earthquake in Fresno County, California should be substantially supplemented to provide description of the energy and ground shaking associated with this event. This is an important example that can be used to provide substantial context for observed subsurface damage rates in proximity to a large seismic event. Expansion of this discussion is important to better inform the UIC regulators on seismic risks. Specifically, the sentence "Subsurface damage, including collapsed or parted well casing, was observed only on 14 of 1,725 active wells" should be supplemented and revised to further state "…less than 1% of the wells suffered damage when exposed to severe ground shaking, corresponding to estimated PGA values on the order of ~0.34g – 0.65g (where g ~ 9.8 m/s2) and PGV values on the order of ~31 – 60 cm/s. In the very few (<10) disposal well sites that appear to have induced seismic events; the energy release and ground shaking has been substantially less than that observed during the May 2nd event in the oil fields near Coalinga. This data serves to inform well integrity failure frequency considering significant levels of ground shaking, and highlights the very low risk of well failure under moderate-level or low-level ground shaking conditions. The draft report should also note and reference the USGS information that is the basis for the above clarification (it is readily available from the USGS): a) The USGS website characterizes the May 2, 1983, earthquake in Fresno County, California as M6.4 event, with reference available at: ….

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Review	1. Appendix C, Pg. 2 Both faults and joints have movement, joints do not have shear movement.
Review	2. Appendix C, Pg. 5 Shale is not always ductile. When shale is hydrofractured to release natural gas, this is a brittle process. They are certainly more brittle than the unconsolidated sediments discussed in the following paragraph. I do not think there should be a distinction of which rock type is easier to induce earthquakes.

Class	**Heather Savage** *Academic Laboratory*
Review	3. Appendix C, Pg. 5 "Earth stress reaction" is an awkward phrase. I think "Crustal deformation" might be better.
Clarify	4. Appendix C, Pg.5 The USGS Quaternary fault map does not seem particularly relevant to the induced seismicity problem. Specifically, most of the induced seismicity we have seen in the past few years occurs on ancient faults that would never have appeared on these maps. Indeed, some of the faults that have been activated did not appear on any map. As is stated in the document, the Quaternary fault map only includes faults that have hosted earthquakes above a M6, which is also irrelevant to induced seismicity we've seen to date.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Group-Scope	1. C-1 Basic Earth Science Concepts In areas where geothermal "hot spots" are proximal to deep will disposal, it may be difficult to discern whether increased seismicity detection levels are due to the injection or whether they result from natural actions where the estimated hypocenters are near the boundaries between the two. When the estimated hypocenters are well below the disposal zone into the "hot spot", this may even be more problematic and there may be difficulties distinguishing between the two.
No Response	2. C-6 Basic Seismology As stated in previous comments, while surface seismic data may be helpful, they are not definitive tools for the locating of all faults.
Clarify	3. C-6 Basic Seismology It should be noted that the surface shaking associated with seismic waves is also a function of the hardness of the rock near the surface.

COMMENTS ON APPENDIX D: PETROLEUM ENGINEERING

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
No Response	1. The reservoir analysis approaches suggested by the NTW provide a sound and rationale basis to evaluate data that is routinely collected as part of injection well operations, and further recognizes in many instances that quality control of the data may be variable for a variety of reasons. The Hall integral analysis suggested by the NTW is a standard engineering approach for evaluating radial flow (injection) behavior; and departures from ideal radial flow may manifest itself by changes of slope on the plot of cumulative injected volume and the Hall Integral and Derivative plots.
Review	2. While the analysis techniques do not provide a unique (or even necessary and/or sufficient) indicator for apriori predictions to identify if seismicity may be induced from a specific injection operation; the techniques may yield useful insights when evaluating, on a "post-mortem" basis, whether injection operations may have departed from ideal radial flow and potentially reached a less permeable fault boundary (and hence could have contributed to the subsurface stress perturbation of sufficient size to induce fault slip). a. The lack of solution uniqueness and the inherent range of uncertainties in reservoir and bottomhole pressure measurements, coupled to the extended time duration needed to observe trends, limit the practical extent that the methods may be applied in managing risk of induced seismicity. The analytical techniques should be viewed in the context that they provide one more tool available in the assessment "toolkit"; but are not reliable for use as "early warning" systems; as many other subsurface factors may be present that lead to departure of pressure behavior from ideal radial flow conditions. b. These point should be better emphasized in the main body of the report in the Section "Petroleum Engineering Applications for Evaluating Induced Seismicity" and also in Appendix D.

Class	**Kris Nygaard** *Oil/Gas Industry*
Group-Scope	3. While the report discusses well-known reservoir engineering calculations that can be used to evaluate how injection may depart from ideal radial flow behavior, the report does not discuss in substantial detail the complex coupling of reservoir flow and reservoir geomechanics that drives the overall physics and modeling of the phenomena. a. Fault activation is governed by the complex interactions between reservoir flow/transport/pressure disturbances and the local dynamically evolving geomechanical loading in proximity to the fault when considering the full system description. b. Stress changes that could activate faults can be transmitted not only by pressure communication from the injection source as considered here, but also via stress communication from the injection source to the fault location. These possible transmission mechanisms (pressure and stress) are clearly coupled and ultimately require sophisticated models that include both effects. c. There are varieties of complex coupled reservoir/geomechanics simulators available and in use by academic, government, and industry researchers.

Class	**Kris Nygaard** *Oil/Gas Industry*
Group-Scope	4. The report could be strengthened by highlighting that there exists coupled advanced geomechanics/reservoir modeling capabilities which could potentially be accessible for specific evaluation of alleged cases of induced seismicity. These advanced models use more representative physics-based modeling than just the simple analytical models as discussed in the present report. It is noted EPA has actually used these types of models to better inform its research on the currently ongoing EPA "Study of Hydraulic Fracturing for Oil and Gas and Its Potential Impact on Drinking Water Resources". The EPA supported studies are available online at: http://www2.epa.gov/hfstudy/modeling-fault-reactivation-and-induced-seismicity-during-hydraulic-fracturing-shale-gas http://www2.epa.gov/hfstudy/development-tm-coupled-flow-geomechanical-simulator-describe-fracture-propagation-and a) The above papers describe in detail the type of data and modeling that would be necessary for their use. The primary benefit of the advanced geomechanics-reservoir coupled models is a more accurate and faithful representation of the complete system; providing improved ability to evaluate potential scenarios that are creating subsurface stress perturbations in proximity of a fault. The disadvantage is that the model development takes more time and requires a higher level of technical skill than the analytic models discussed in the report. The disadvantage of the analytic models discussed in the report is that these do not consider the relative stress perturbations that may be created by the injection; therefore, there is no ability to use the analytic models to understand the complex stress field perturbations that exist, and the relative magnitude of stress perturbations that may be attributed to the disposal operation.

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Clarify	1. The pressure data collected by the well operators is a key component to identifying where induced seismicity may soon occur. I want to make a point of mentioning that the quality and availability of these data can vary widely. In the same vein, the case of Youngstown, Ohio is highlighted as one in which the well operators provided daily pumping records. Most of the case studies mentioned here also have fairly detailed pumping records. To my knowledge, daily records are not required to be reported anywhere right now. Furthermore, even on the state level, the ease of accessing injection information can be quite different. The report highlights the Texas Railroad Commission as one of the state agencies that runs a database with this information, however, Texas has one of the better sites. Furthermore, some states, like Oklahoma, have limited online information, or websites that make the data difficult to access except on an individual well by well basis. As this report emphasizes, monthly (or more frequent) pumping records are essential for seeing any changes in reservoir pressure or flow rate that may indicate that faulting or fracture is taking place within the reservoir. Daily records would be better but are not usually made available. Combining daily pumping records with continuous, well-located seismicity would be a powerful tool for monitoring and mitigating induced seismicity. But relying on what is currently reported is going to mean coming up with a way to make reporting in some states more reliable and easier to access.
Clarify	2. Appendix D, Figure 9 The comparison of cumulative seismicity to the Hall Integral needs a better defined purpose, and the challenges sound like challenges associated with any seismic monitoring, not necessarily related to the Hall Integral. I am not sure if the example plot is supposed to demonstrate an example of the seismicity and the Hall integral showing a correlation, but it does not do so convincingly. Perhaps if seismicity rate were plotted instead, or if the plot was done as Hall Integral vs. cumulative seismicity, then changes in slope would be easier to see.

Class	**Heather Savage** *Academic Laboratory*
Clarify: a-c; Review: d; Outside Scope: e-f	3. Appendix D, Figure 10 I do not think that plotting station number as a variable on this plot effectively conveys how seismicity rate may change with station coverage. a) For instance, how does the number of stations in the time around January 10 vary so dramatically? b) Was station coverage really changing that significantly on a weekly or monthly basis? c) Why are those points so close together? d) I think a more effective plot to make to deal with the issue of seismicity rate change with station coverage is to plot all of the events with magnitude on the y-axis and time on the x-axis (this is often referred to as a stick plot). Number of seismometers over time can be displayed along to x-axis. Although changes in station coverage is of course a concern when considering seismicity rates, the most profound change when additional stations are installed is the number of small events that are recorded. e) If there are much more numerous small events when there are more stations, then some correction may be needed. In order to account for this, the magnitude of completeness should be calculated. This is the minimum magnitude for which there is confidence that all of the earthquakes have been reported, usually by plotting the Gutenberg-Richter distribution. Once that minimum magnitude of completeness is determined at the time when the fewest stations existed, this should be the cutoff to compare seismicity at all time periods. f) If seismicity rate still increases with time, it is due to an actual increase in seismicity.
Clarify	4. Appendix D, Pressure transient testing for disposal wells This section feels weaker than the others. There is too much emphasis put on the “log-log” plots providing “mathematical pictures”. Log-log plots are not inherently special, and are not required because one is considering a partial differential equation. It useful to plot data in log-log space when both parameters will vary over many orders of magnitude. Furthermore, I cannot determine by the plots shown here why any of these analyses cannot be performed using excel. Although it would certainly be easier with a more sophisticated tool, it can still be accomplished in excel.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
No response	1. D-3 Petroleum Engineers Information Collection General comment – While petroleum engineering methods can be useful to an analysis of conditions, they are by no means definitive and the results from such should be used with caution. a) While the use of reservoir engineering tools can provide value as part of an overall analysis of disposal wells operations conditions, there are a number of caveats with their use and value that should be considered when applying these tools. b) It also should be recognized that the use of some of these tools and the analysis of data derived from their use may provide differing value depending upon when they are utilized in the lifetime of a well. c) The NTW has done an excellent job of laying out some of the challenges associated with use of these tools.
Clarify	2. D-6 Operational Data Plots and Analysis It would be useful to have Hall plots for disposal wells where there is no record of induced seismicity for comparative purposes. It may be common for most injection wells to have increased injectivity over time.
No Response	3. D-16 through D-19 Overview of Pressure Transient Testing It is quite useful that both the challenges and red flags associated with the use of any of these methods have been identified.

COMMENTS ON APPENDIX E: TEXAS CASE STUDY

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Review	**5.1 Case Study Selection** 1. I think there is a glaring oversight in this document in terms of the case studies that were chosen. The case studies discussed are the most clear-cut cases of induced seismicity in the last few years. The seismicity began shortly after the disposal well began pumping, earthquakes were located in space and associated with a single, specific well, and in some cases operators shut down pumping and earthquakes began to tail off. These were the easiest cases to deal with in some sense. The more difficult situations are the ones that are less clear cut but still extremely compelling as examples of induced seismicity, such as Prague, Oklahoma, Trinidad, Colorado, and Snyder, Texas. In these cases, the onset of pumping and the onset of seismicity were offset by long time periods, sometimes years. Still, the uptick in seismicity indicates that non-natural events are occurring.

Class	**Heather Savage** *Academic Laboratory*
Group-Scope	2. To fix this, I would add a case study involving a site in Oklahoma. Oklahoma now has more earthquakes per square mile than California (Keranen et al 2014), and is only mentioned once in this document as a place where induced seismicity may be occurring. Furthermore, Oklahoma has had the largest midcontinent earthquakes associated with injection that we've seen to date. There are several sites of increased seismicity including Prague, Jones, and Enid. a. The cases in Oklahoma have been more controversial, because oil and gas activities have been ongoing in the state for decades and there is some argument that there is no reason for seismicity to begin now, but that is not necessarily true for several reasons. b. First, the volumes being injected in some places have become enormous, such as in the area around Jones, OK. c. Furthermore, some of these sites experience longer-term pressure build up, with faults only becoming critically stressed in the few months before moderate sized earthquakes (van der Elst et al. 2013). d. Although these complexities make analyses more difficult, the mounting number of earthquakes in these regions means that we must find a way of dealing with these less straightforward cases.
Review	**4.6 North Texas Cases** 1. It seems as though the earthquakes mentioned in the DFW case study all occurred in the sedimentary rocks? This is in line with my earlier comments regarding that faults do not have to be hosted within basement rocks to have earthquakes.
Clarify	2. The figures should be integrated with the text, as is done throughout the rest of the document. It is very hard to read with all of the figures (which are quite detailed) at the end.
Review	3. There needs to be a clearer description of what was learned from the various pumping tests performed. Which wells showed anomalies? Where are they in reference to the earthquakes? All of this information is in there, but it is not presented in a way that is clear to the reader.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Review	1. E-8 There will be some doubts that the 2013 and 5/15/09 events were related to the injection because of the significant depth of the hypocenters reported. As such, it would have been useful for this to have been noted.
Review	2. E-20 North Texas Area Lessons Learned Fifth bullet – What is meant by many areas? a. Just the presence of additional monitoring stations does not guarantee that active faults will be found. Additional monitoring stations may be warranted when there is some indication of previously unreported seismic activity.

COMMENTS ON APPENDIX F: ARKANSAS CASE STUDY

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Clarify	1. The reference to the New Madrid Seismic Zone as part of the historical seismicity in Arkansas is out of place. That region is far from the activity in the Guy area, and the statement is misleading.
Review	2. Appendix F, Pg.7 There are some question marks at one of the bullets where a figure number should be.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Clarify	1. F-14 Lessons Learned The same as with previous comments provided earlier, while understood, the Arkansas moratorium obviated any opportunities for further scientific insight into the events here or determining whether the shallower disposal wells were contributing to the induced seismicity or not.
Review	2. F-16 Figure F-2 It is unclear that any disposal into the Kissinger, Brown or SRE wells may have reached the basement rock and contributed to induced seismicity. As they are shown on the same figure, this may leave the casual reader with the impression that it is clear that they did so when it is believed that no confirmation of such is provided.
Review	3. F-17 Figure F-3 While it is understood that this figure was pulled from a publication, there is no correlation provided as to how Well #1 or Well #5 relate to the wells shown on the other figures. Without context or other correlation, this would likely be confusing to many readers as to what wells are shown here as no other mention of these particular wells could be found.

COMMENTS ON APPENDIX G: WEST VIRGINIA CASE STUDY

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
No Response	1. Page G-7, Braxton West Virginia Case Study Background a) Suggest including the following reference : Viso, R. F., "Sequential Development of the Gassaway Structure in Braxton County, West Virginia," West Virginia University, MSc. Thesis, 1999. b) With the above reference considered, suggest revising the discussion to include the geologic description of the Gassaway Structure and the understanding that geologic information was available in the public domain. A learning that could be captured is the use of broad literature searches, including academic publications in the area of interest may provide valuable local knowledge.

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
Review	1. Appendix G and other places: The text on the geologic maps and cross-sections are generally too small to read.
Clarify	2. The details of the seismicity in this section are fewer than in the other case studies. Has no one relocated this seismicity or associated it with any known faults?

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
No Response	It is noted that no reported faults were identified in the case study summary and that the injection occurred into a horizon far above basement rock making this the weakest by far of the four case studies.

COMMENTS ON APPENDIX H: OHIO CASE STUDY

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Clarify	There is no reason given as to why the Northstar wells were drilled into the Precambrian basement when they were only permitted into the Mount Simon Sandstone. Did the company deliberately violate their permit conditions? It would be interesting and useful to understand why drilling to this depth occurred.

COMMENTS ON APPENDICES I THROUGH L

BY ROBIN MCGUIRE, CONSULTANT

Class	**Robin McGuire** *Consultant*
No	**Appendix K: Subject Bibliography** A reference that should be mentioned is the following: W.L. Ellsworth, "Injection Induced Earthquakes," Science, 12 July 2013: Vol. 341 no. 6142

BY CRAIG NICHOLSON, ACADEMIA

Class	**Craig Nicholson** *Academia*
add	**Appendix K: Subject Bibliography** Committee on Induced Seismicity Potential (2012) in Energy Technologies, Induced Seismicity Potential in Energy Technologies, National Research Council, Washington, DC; http://dels.nas.edu/Report/Induced-Seismicity-Potential-Energy-Technologies/13355. Keranen, K. M., H. M. Savage, G. A. Abers, and E. S. Cochran (2013), Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence, Geology, G34045.1, doi:10.1130/G34045.1. McGarr, A., 2014, Maximum magnitude earthquakes induced by fluid injection, Journal of Geophysical Research Solid Earth, v.119, doi: 10.1002/2013JB010597.
no	Ellsworth, W.L., 2013, Injection-induced earthquakes, Science, v.341, 1225942, doi: 10.1126/science.1225942, p.142. Zoback, M.D., 2012, Managing the seismic risk posed by wastewater disposal. Earth Magazine v.57, p.38–43

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
add	**Appendix K: Subject Bibliography** 1. Page K-2, Educational Websites on Seismicity Suggest including link to the he USGS Earthquake Hazards Program "ShakeMap" internet site. ShakeMap sites provide near-real-time maps of ground motion and shaking intensity following significant earthquakes. The information, maps, and data available at this website provide ability to identify and estimate ground shaking levels associated with seismic events: http://earthquake.usgs.gov/earthquakes/shakemap/

Class	**Kris Nygaard** *Oil/Gas Industry*
add	2. The Ground Water Protection Council remains active on coordinating and facilitating discussions across a variety of stakeholder groups, and has an internet site that provides publications on the topic to inform the public and stakeholders: http://www.gwpc.org/resources/publications
Add hyperlink	3. Page K-4, General Information and Protocols Include reference to "White Paper II Summarizing a Special Session on Induced Seismicity" based on a special session entitled "Assessing & Managing Risk of Induced Seismicity by Underground Injection" held at the Ground Water Protection Council's 2013 Annual Forum, St. Louis (Sep 23-25). The white paper, authored by John Veil, is available at: http://www.gwpc.org/resources/publications
add	4. Page K-10, West Virginia Include reference to Viso, R. F., "Sequential Development of the Gassaway Structure in Braxton County, West Virginia," West Virginia University, MSc. Thesis, 1999.

Class	**Kris Nygaard** *Oil/Gas Industry*
Add per final consensus	5. Page K-16, Protocols and Risk Analysis This section should include reference to the ExxonMobil paper that describes risk assessment, risk mitigation, and risk management of injection related induced seismicity (this paper is currently listed as reference on p. K-4 in the section "General Information and Protocols", but would be better suited for listing as a reference in the "Protocols and Risk Analysis" reference section. a) Nygaard, K. J., J. Cardenas, P. P. Krishna, T. K. Ellison, and E. L. Templeton-Barrett, 2013, "Technical Consideration Associated with Risk Management of Potential Induced Seismicity in Injection Operations", 5to. Congreso de Producción y Desarrollo de Reservas, Argentina, May 21 -24, 2013. b) To improve the clarity, usefulness, and ease of access of the reference listing, the "General Information and Protocols" section (p. K-4) should be re-labeled as "General Information" and all "protocol-related" references should appear listed in the Protocols and Risk Analysis Section (p. K-15). This will help the reader more readily identify relevant reference sources specifically related to risk management.

	1. Page K-18, Technical or Technology Include the 2013 study that illustrates that the presence of a basal seal has a potentially important effect on reducing pressure increases in the crystalline basement, decreasing the risk of an induced seismic event. a) Zhang, Y., Person, M., Rupp, J., Ellett, K., Celia, M., Gable, C., Bowen, B., Evans, J., Bandilla, Mozley, P., Dewers, T., Elliot, T. Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injections into basal reservoirs. Groundwater, NGWA, June, 2013. Paper available at: Zhang, Y., Person, M., Rupp, J., Ellett, K., Celia, M., Gable, C., Bowen, B., Evans, J., Bandilla, Mozley, P., Dewers, T., Elliot, T. Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injections into basal reservoirs. Groundwater, NGWA, June, 2013. b) Include the recent study has been published in 2014 that illustrates that the subsurface complexity and that many factors may lead to induced seismicity Amos C.B., Audet, P., Hammond, W.C., Burgmann, R., Johanson, I.A., Blewitt, G. (2014) "Uplift and seismicity driven by groundwater depletion in central California", Nature 509, 483–486 (May 22). Paper available at: http://www.nature.com/nature/journal/v509/n7501/full/nature13275.html c) Include references that describe ground shaking relationships associated with seismic events, specifically, two key references are: Wald, D. J., Quitoriano, V., Heaton, T. H., Kanamori, H. (1999) "Relationships between peak ground acceleration, peak ground velocity, and modified mercalli intensity in California", Earthquake Spectra, 15: 557 – 564 Wald, D. J., Worden, B. C., Quitoriano, V., and Pankow, K. L., Advanced National Seismic System, "ShakeMap® Manual, Technical Manual, Users Guide, and Software Guide", Version 1.0 (June 19, 2006). Available from the USGS at: http://pubs.usgs.gov/tm/2005/12A01/pdf/508TM12-A1.pdf 2. A second "white paper" that summarizes the status of knowledge and approaches for assessing and managing the risk of induced seismicity, has been developed based on a special session entitled "Assessing & Managing Risk of Induced Seismicity by Underground Injection" held at the Ground Water Protection Council's 2013 Annual Forum, St. Louis (Sep 23-25). The white paper, authored by John Veil, is available at:

Class	**Kris Nygaard** *Oil/Gas Industry*
	White Paper II Summarizing a Special Session on Induced Seismicity +Zhang, Y., Person, M., Rupp, J., Ellett, K., Celia, M., Gable, C., Bowen, B., Evans, J., Bandilla, Mozley, P., Dewers, T., Elliot, T. Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injections into basal reservoirs. Groundwater, NGWA, June, 2013. This paper is available online at: Zhang, Y., Person, M., Rupp, J., Ellett, K., Celia, M., Gable, C., Bowen, B., Evans, J., Bandilla, Mozley, P., Dewers, T., Elliot, T. Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injections into basal reservoirs. Groundwater, NGWA, June, 2013.

BY HEATHER SAVAGE, ACADEMIC LABORATORY

Class	**Heather Savage** *Academic Laboratory*
	1. I think that all of the appropriate data sources have been identified.

BY ED STEELE, OIL/GAS INDUSTRY AND CONSULTANT

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Add	1. In any such undertaking that transpires over an extended length of time, there will inevitably be publication of new research that can provide value for consideration. As academic and industry interest in induced seismicity has risen, there has been a concomitant increase in workshop, conferences, and symposia dedicated to this subject. As such, any point-in-time exercise as the NTW effort should provide recommendations way forward that are flexible enough to consider the findings from additional research and studies. Additional Selected Suggest References: McGarr, A 2014, Maximum magnitude earthquakes induced by fluid injection, Journal of Geophysical Research: Solid Earth, American Geophysical Union. Costain, J.K, G.A. Bollinger and J. A. Speer 1987, Hydroseismicity – A hypothesis for the role of water in the generation of intraplate seismicity, Geology v. 15, pp. 618-621. Costain, John K. and G.A. Bollinger 2010, Review: Research Results in Hydroseismicity from 1987 to 2009, Bulletin of the Seismological Society of America, vol. 100, No. 5A, pp. 1841-1858. Simpson, D.W., W.S. Leith and C.H. Scholz 1988, Two Types of Reservoir Induced Seismicity, Bulletin of the Seismological Society of America, vol. 78, No. 6, pp. 2025-2040. Talwani, Pradeep 1997, On the Nature of Reservoir Induced Seismicity, Pure and Applied Geophysics 150, pp. 473-492. Flewelling, Samuel A. and Manu Sharma 2014, Constraints on Upward Migration of Hydraulic Fracturing Fluid and Brine, Groundwater, Vol. 52, No. 1, pp. 9-19. Zoback, M.D. et al 2003, Determination of stress orientation and magnitude in deep wells, International Journal of Rock Mechanics and Mining Sciences 40, pp. 1049-1076. Galybin, A.N., S.S. Grigoryan and Sh. A. Mukhamedeiv 1998, Model of induced seismicity by water injection, SPE/ISRM 47253. Hurd, Owen and Mark D. Zoback 2012, Intraplate earthquakes, regional stress and fault mechanics in the Central and Eastern U.S. and Southeastern Canada, Tectonophysics 581, pp. 182-193 Bonilla, M.G., R.K. Mark and J.J. Lienkaemper 1984, Statistical Relations Among Earthquake Magnitude, Surface Rupture Length, and Surface Fault Displacement, USGS Open-File Report 84-256, Version 1.1.

Class	**Ed Steele** *Oil/Gas Industry and Consultant*
Add	Rutqvist, Jonny, et al, 2013, Modeling of Fault Reactivation and Induced Seismicity During Hydraulic Fracturing of Shale Gas Reservoirs, Journal of Petroleum Science and Technology 107, pp. 31-44.
Clarify	4.10 Appendix I: Aseismic Examples Is there a reason why the wells involved in the examples cited are not named and located? This could be helpful if someone had more information to add and the information provided is not consistent in form with the case studies.
Clarify	4.11 Appendix J:Paradox Valley There is a wealth of information available that could have been provided here. Is there any reason why this section was kept so brief?

COMMENTS ON APPENDIX M: USGS COLLABORATION

BY KRIS NYGAARD, OIL/GAS INDUSTRY

Class	**Kris Nygaard** *Oil/Gas Industry*
clarify	a) The USGS has developed an informative and substantial body of literature and information on ground shaking levels associated with seismic events, and the correlation of ground shaking values (e.g., PGA / PGV values) to the Modified Mercalli Scale and other magnitude scales. There is significant omission in the draft report that this information is not effectively summarized in the main body of the report or Appendix M. b) Informing the UIC regulators, stakeholders, and broad public on the actual ground shaking levels that may be expected with publicly reported magnitudes from monitoring systems is critical to ensure proper understanding of the hazard. Appendix M and/or the main body of the report should be revised to provide a summary of the information developed by the USGS related to ground shaking characterization and correlation of ground-shaking metrics to magnitude measurements. The type of detailed information is readily available on the USGS website and could be readily included in the current report. http://earthquake.usgs.gov/earthquakes/shakemap/background.php http://earthquake.usgs.gov/learn/topics/mag_vs_int.php

APPENDIX O: RESPONSE TO PEER REVIEW COMMENTS RELEVANT TO THE TOPIC BUT OUTSIDE THE SCOPE

General Scope Discussion O-2
Definitive Cause and Effect O-2
Authority O-3
Outside Scope O-3
Generalized Considerations / Lack of Clear Cut Threshold Criteria In The Decision Model O-4
Risk Assessment Analysis / Ground Shaking O-4
Detailed Fault Analysis O-4
Seismological Analysis O-5
Clarifications O-5
Miscellaneous Comments O-5
UIC Program Related Details O-8
Pressure Influences O-9
Injection Volume O-11
Petroleum Engineering Approaches O-12
Flow Paths, Fracture Flow, and Fault Movement O-14
Report Recommendations O-17
Historic Seismicity O-20
Stop Light aka Traffic Light O-21

All specific comments, sorted by report section and reviewer and classified by response category, are included in APPENDIX N. APPENDIX A represents a subset of APPENDIX N, to specifically address comments not reflected in changes made to the document. The categories specifically covered in this Appendix are shown below:

a. Authority: Those comments related to the applicability of EPA authority.
b. Scope: Those comments outside the purpose of the report (providing a practical underground injection control (UIC) management tool), including recommendations for policy changes, new regulations, extensive research, or other time-prohibitive additional studies, such as complex, proprietary modeling.
c. Clarify: Those comments relevant to the topic and that request additional clarification, but the clarification is not needed by the intended report recipients, the UIC program staff. These comments can be addressed by directing the commenter to the appropriate place in the report, or providing additional UIC program background information.

When specific comments are cited below they are treated as follows: (initials of the reviewer: the report section- comment number in APPENDIX N). Comments are quoted exactly, without corrections.

General Scope Discussion

A wide range of comments was received that included not only opposing viewpoints but also requested additions to the report, ranging from very detailed items to new topics (KN: App D-3a-c & 4; HS: App E-2). Additional recommendations for the Report Findings section of the report are discussed under Clarifications: Report Recommendations below. The National Technical Workgroup (NTW) task was to develop *practical approaches* that can be used immediately by UIC program staff and management. Many of the comments and recommendations in the Scope category were deemed impractical and therefore beyond the stated purpose of the effort. For example, the task objectives do not include projects involving additional research nor developing practices that are beyond the regulatory authority of UIC programs. Another recurring topic was the need for more research to reach a level of certainty before action. This topic is addressed below in the Definitive Cause and Effect section.

One consideration for whether to incorporate comments into the revised document was the intended audience, primarily UIC management and staff. Another consideration was the need to meet the timetable for report completion, even though the number of publications on induced seismicity is constantly expanding. The report case studies and their updates were fixed with respect to the timeframe, as discussed in the report. Regarding definitions of terms, the meanings associated with common usage of UIC or petroleum terminology were intended, with more complete definitions provided in the Glossary of Terms or in additional commentary during the relevant discussions.

Definitive Cause and Effect

Injection-induced seismicity has been well documented (Nicholson and Wesson, 1990) over the decades through petroleum industry case studies and research at Rocky Mountain Arsenal, Rangely Field, Ekofisk, and Basel Switzerland, to name widely accepted examples with multi-disciplinary approaches. While it is not common, long distance pressure communication does in fact occur, as shown in APPENDIX I. By the same token, decades of disposal and oil field activity clearly indicates that the recent increase in seismic activity in production areas (which include disposal wells) cannot be characterized with broad generalizations.

Definitive proof of induced seismicity caused by disposal in a specific well is not realistic considering the uncertainty in the determinations of seismic event hypocenters and the lack of

available high-quality information (operational and subsurface or possibly proprietary). The risk of litigation further complicates the situation. Numerous methods are available in the field of petroleum engineering and geoscience to analyze probable flow paths, pressure effects, and subsurface geometry. However, these data are generally expensive to acquire, requiring land access and trained personnel to acquire and analyze the results. Detailed information, such as 3-D surveys, is usually only acquired by medium or large exploration and production companies. UIC program staff generally have no access to this information, nor the software and training to make best use of such data.

Practical, simple methods for determining linear (fracture/fault) flow combined with knowledge of the particular formation and major structural lineaments are the best indicators of a potential induced seismicity problem. Assistance from subject matter experts with respect to local seismology or specific area operations would be invaluable to the UIC Program staff or management investigating the potential problem.

AUTHORITY

Several reviewers (JB: ES-1, 2 & 3, Main-4 & 5; and ES: Main-4) questioned EPA authority to consider seismicity issues, citing lack of USDW contamination cases. Other reviewers wanted more stringent injection well regulatory requirements. The NTW was tasked with preparing a technical document to assist injection well regulators. Creation of additional rules or official guidance was outside the NTW's charge, as are policy matters for this issue.

As the report discusses, EPA has primary regulatory responsibility for fluid injection under the Safe Drinking Water Act (SDWA), which does not address induced seismicity directly. The SDWA gives EPA authority to regulate injection activity for the purposes of protecting underground sources of drinking water. Regulation could include considerations to prevent induced seismicity from interfering with containment of injected fluids underground or from damaging infrastructure on the surface. Injection with the potential to induce seismicity and contaminate USDWs therefore falls under the authority of the UIC program.

OUTSIDE SCOPE

Several themes were repeated throughout the reviewers' comments, and were grouped for easier response below. The comments in these themes were deemed outside the NTW charge.

Generalized Considerations / Lack of Clear Cut Threshold Criteria In The Decision Model

Some comments requested more explicit decision criteria and threshold response actions in the decision model, (JB: Main-18, 21, 23, App B-1; RM: Main-8; ES: App C-1, App D-3. This topic is essentially covered in the General Scope Discussion, i.e., the need for practical approaches that take into account the variability of seismic response across the country within the different UIC program requirements. Because of complex variations in geology and reservoir characteristics across the country, it is neither practical nor appropriate to provide a prescriptive step-by-step decision model.

Risk Assessment Analysis / Ground Shaking

A number of recommendations were made to include a comprehensive (formal) risk assessment in lieu of the risk management process outlined in the decision model, (JB: ES-8, 8a; Main-4, 20, 21, 23 App. C-1; KN: Main-2, 16, 17a, App. C-1, 2, App M-a & b). Through case examples, the report illustrates situations where existing program requirements provided sufficient information for the program manager to assess the possibility of addressing induced seismicity without the need to undertake a formal risk assessment.

UIC programs use permit analysis to effectively address risks to a USDW in a timely fashion. Therefore, long term formal risk assessments with complex modeling and research in regard to minimizing and managing induced seismicity are not practical.

With respect to adding impact criteria such as degree of damage, shaking or ground acceleration to the decision model, there are two fundamental issues. First, low population or a lack of structures does not change the need for USDW protection. Second, in early discussions with USGS staff, it was pointed out that the USGS ground acceleration maps (the National Seismic Hazard Maps) were designed for use by insurance companies and engineers in regard to surface installations. The maps are based on ground motion at the surface. It was stated that motion at the surface was roughly twice that of below ground. At the time of the conversation, 2011, the database for the hazard maps was restricted to only natural seismic events. Due to hazard map design criteria and focus on natural events, the EPA was advised by USGS not to use them.

Detailed Fault Analysis

Many of the reviewers (CN: Main-7; HS: Main-1, App. C-4; KN: App D-3a-c, 4) offered additional facts for inclusion, along with differing views of current stress, stress regime, orientation (fault and stresses) and basic availability of adequate information. The definition of a Fault of Concern was revised based in part on these comments.

As acknowledged in 0Rock Mechanics and APPENDIX M: Deep Stress Fields, the science around fault movement is quite complex and available information is rarely sufficient to provide detailed answers. As noted above, complex modeling and potential theories are outside the scope of a practical tool for UIC regulators. From a practical standpoint, given the difficulty of understanding the subsurface structure, having an approximate idea of what fault strike (horizontal orientation) has the most potential for movement, is about as good an indicator of potential seismicity as there is without a map of active faults (e.g., the USGS Quaternary Fault and Fold Maps).

Seismological Analysis

Several reviewers recommended specific seismological analysis (timing, Gutenberg-Richter distribution, etc.). This is an area outside the scope of this report. (ES: Main-20; HS: App. D-3e & 3f)

Clarifications

The following responses cover comments requesting either additional explanation or program specific background to cover the concern expressed. Additions were not made to the report for these specific comments, however, in some instances statements were revised for clarity.

Miscellaneous Comments

The clarification follows each comment.

1. There has been an earthquake in Ohio recently that is strongly suspected to be hydrofracture-related. (HS: Main-2)

    - This event is outside the report timeline and hydraulic fracturing is not the focus of this report. In addition, the report reference to seismicity related to hydraulic fracturing was only to mention that risk of felt seismicity was less at hydraulic fracturing sites and to cite some examples.

2. APPENDIX D, Figure 10 I do not think that plotting station number as a variable on this plot effectively conveys how seismicity rate may change with station coverage. For instance, how does the number of stations in the time around January 10 vary so dramatically? Was station coverage really changing that significantly on a weekly or monthly basis? Why are those points so close together? (HS: App. D-3a-c)

- The number of stations reflects the establishment of temporary networks to study the occurrence. In turn, these networks picked up many more small magnitude events.

3. It should be noted that the events related to hydraulic fracturing in British Columbia occurred in strata that were very close to basement rock and this is not typically the case with most current hydraulic fracturing operations in the US. As such, these events may be an artifact of the geologic conditions found here and are not generally reflective of conditions found in US based operations. (ES: Main-2)

    - Seismicity is a function of local stress conditions and geology. The NTW has no knowledge that similar conditions to those cited above do not exist in the United States.

4. Another general concern that I have is that I think there is way too much emphasis in the report about basement faults. Although many seismically active faults occur within basement rocks, this is not a prerequisite. Because fluid pumping generally occurs within sedimentary sequences, which also have many faults, it is reasonable to assume that either seismic or aseismic processes may begin where the fluid pressures are highest in the sedimentary rocks (i.e., nearer to the well). The 2011 Prague, Oklahoma sequence appears to have started within the sedimentary cover, at least a kilometer above the basement. Some aftershock seismicity continued to within ~250 m of one of the disposal wells (Keranen et al. 2013). I think the suggestion in APPENDIX B that the depth to basement near a well may be considered in terms of choosing an appropriate site is overstated. (HS: Main-17)

    - The NTW does not consider the hydraulic communication with basement to be overstated, based on the analysis of the selected case studies and the literature review. However, the phrasing in APPENDIX B was revised to better reflect the NTW's intended meaning.

5. Earthquakes generally occur on pre-existing faults, and there is no brittle failure of intact rock. (An exception is during hydraulic fracturing, which is designed to fracture intact rock.) Thus brittle failure does not cause fault slip; fault slip causes strain energy to be released in the form of seismic waves. If "brittle failure" is used as a synonym for fault slip, that is not standard in seismology, and is not consistent with the quote (below), which says that one causes the other. ("An earthquake (seismic event) occurs when there is brittle failure along a fault at depth. The resulting brittle failure of the fault results in

slip or displacement that generates elastic waves that propagate away from the fault. The event can be from a source in, on, or above ground that creates a wave motion in the earth.") (RM: App. C-1b)

- Brittle failure is a basic rock mechanics description; however, the section has been revised for clarification.

6. The figures should be integrated with the text, as is done throughout the rest of the document. It is very hard to read with all of the figures (which are quite detailed) at the end. (HS: App. E-2)

   - It was attempted, but it was beyond the ability of the software used. The figures have been revised but are still best read in digital format where they can be enlarged.

7. The reference to the New Madrid Seismic Zone (NMSZ) as part of the historical seismicity in Arkansas is out of place. That region is far from the activity in the Guy area, and the statement is misleading. (HS: App. F-1)

   - The authors of the original study, Horton and Ausbrooks (2011), pointed out the similarity between the seismic stresses in the Central Arkansas area and the New Madrid Seismic Zone.

8. F-14 Lessons Learned The same as with previous comments provided earlier, while understood, the Arkansas moratorium obviated any opportunities for further scientific insight into the events here or determining whether the shallower disposal wells were contributing to the induced seismicity or not. (ES: App. E-1)

   - The moratorium on disposal activity was a precautionary step that addressed significant public concerns. After the moratorium was put in place, seismicity in the immediate area significantly declined.

9. The details of the seismicity in this section (App G West Virginia) are fewer than in the other case studies. Has no one relocated this seismicity or associated it with any known faults? (HS: App. G-2)

   - Correct, at the time of this report, there has been no local network added to investigate the sporadic seismicity, and there have been no relocations.

10. There is no reason given as to why the Northstar wells were drilled into the Precambrian basement when they were only permitted into the Mount Simon Sandstone. Did the company deliberately violate their permit conditions? It would be interesting and useful to understand why drilling to this depth occurred. (ES: App. H-1)

    - The reviewer's assumption is incorrect. As noted in the text, the well was drilled to the Precambrian for a stratigraphic test. The well was permitted to inject from the top of the Knox through 200' of Precambrian. For more information on the stratigraphic test, see the section on "Piggyback Logging" at Ohio Department of Natural Resources (2012) (http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/UICReport.pdf)

11. APPENDIX I: Aseismic Examples: Is there a reason why the wells involved in the examples cited are not named and located? This could be helpful if someone had more information to add and the information provided is not consistent in form with the case studies. (ES: App. I)

    - APPENDIX I does not reflect induced seismicity events similar to the Case Studies within the report, but rather provides information on long distance pressure communication potentials. The identifying features were not necessary to convey that information. The identification information was omitted at the request of some NTW workgroup members.

12. There is a wealth of information available (Paradox Valley) that could have been provided here. Is there any reason why this section was kept so brief? (ES: App. J)

    - Since there was already a wealth of information on this site, the authors did not feel the need to reiterate what other researchers have already stated. A number of the additional articles are referenced in the Subject Bibliography in APPENDIX K.

UIC Program Related Details

The UIC program regulates injection into the subsurface, using an area of review and a zone of endangering influence (ZEI). The program is designed to prevent flow into a USDW from the injection interval up potential conduits, such as unplugged wells. For Class II wells, the authorized program varies somewhat but either entails a specific radius of investigation ($^1/_4$ or ½ mile) or a calculated ZEI. The ZEI is generally calculated using the 1967 Matthews and Russell equation

(also shown in the 40 CFR 146.6 in ground water terminology) for a single well injecting into an infinite homogenous and isotropic reservoir.

Following are specific comments received with responses, grouped by categories wherever possible.

1. Existing versus new wells general: In general, available data outlined on page B-4 is not available for existing wells as a lot of the geologic, hydrologic and geosciences data can only be obtained when the well is drilled or completed. In addition, most existing wells will not have seismic data to locate faults in area and if it is available it will most likely be 2D seismic which has poor resolution and rarely 3D seismic data. If the 3D seismic data is available, the 3D seismic data might not be deep enough to map the basement faults because the target of the 3D seismic data is the hydrocarbon producing zone which is typically above the injection zone. (JB: App. B-3)

    - The decision model used by the UIC program manager is based on knowledge of the general area and the specific location of the well. The manager also makes a determination as to whether the geologic information provided by the applicant is sufficient to make a permitting decision. The items that the reviewer pointed out are factors to be considered in the evaluation. The data are not necessarily required in all situations. UIC regulators have at times been invited to view 'private source' seismic data.

PRESSURE INFLUENCES

Injection pressures in Class II UIC wells are generally not permitted above formation fracture pressure. However, this is not a uniform requirement, nor is obtaining existing reservoir or actual fracture pressures for the formation.

Several reviewers discussed calculating the distance of pressure influence. Most UIC programs use a simplified pressure formula suitable for radial, homogenous flow conditions. Oil and gas operators may use other methods, for example, when expediting recovery from a waterflood or other pressure support operations. The information the operators use is generally not available to UIC program staff. See also Petroleum Engineering Approaches below.

Related Reviewers Comments:

1. The use of "pressure build up" in a general sense without defining why or how the pressure build-up occurred could cause the investigator to reach a false positive as to

cause and effect. The injection disposal industry (not just O&G) can see, on a regular basis, the buildup of pressure as a near bore effect related to build up of precipitates associated with water hardness (carbonates) or other chemical reaction that clogs the pores reducing the permeability and causing back pressure. It is for this reason that disposal injection wells may be acidized on occasion to clear the pores and improve injectivity which lowers the injection pressure. (JB: ES-4)

- The commenter appears to be confusing skin effect and fluid flow through reservoir rock. UIC permitting calculations determine the pressure build-up due to fluid flow through reservoir rock only, which in turn sets the permit operating pressure limit. The operating pressure limit effectively addresses any pressure build-up regardless of cause.

2. I get the impression that the writer is relying on buildup of pressure as that actual instigator of induced seismicity thru the creation of a fault. That is false because the buildup of pressure to create a fault is hydraulic fracturing and UIC class II disposal wells are permitted with a maximum injection pressure so as to not exceed the fracture pressure. (JB: ES-4a)

   - As discussed in this report, induced seismicity requires the three components enumerated under the definition of a Fault of Concern.

3. The document does identify pore pressure as the culprit that triggers a seismic event (thus not an induced seismic event but a triggered seismic event) but fails to describe the complete mechanism and this is understandable because the known mechanism is still a theory and requires lots of research. The theory is based upon the belief that a preexisting fault, is held together by insitu stresses that are disrupted by pore pressure and allow the fault to slip. (JB: ES-4b)

   - See Mohr-Coulomb discussion under Rock Mechanics in 0.

4. The definition of faults of concern needs to be more specific with regard to "significant earthquake" (see Variety and Validity of Approaches – comment 2). The definition also needs to include an expansion of the term "optimally orientated" to include a fault whose orientation is such that the direction of the principal insitu stress is at a 30-50 degree angle to the fault plane. The definition also needs to include a statement that the fault must be critically stressed meaning that there is sufficient stored energy (stress) that

should the fault slip, it would generate a seismic event of sufficient magnitude to be detected. (JB: ES-5)

5. Detailed fault discussions are addressed in the opening of this appendix on local variations, Outside Scope: Detailed Fault Analysis. Additionally, the suggested specific range of fault angles is open to a wide variety of interpretation as described in the collection of publications in *Faulting, fracturing and igneous intrusion in the earth's crust*, edited by D. Healy, R. W. H. Butler, , Z. K. Shipton and R. H. Sibson; London : Geological Society of London, 2012. (@Geological Society, London, Special Publications), (ABES)164039384.
6. I agree that disposal wells have a greater potential for pressure buildup but nowhere in this document to you state that pore pressure dissipates as you move away from the well (pore pressure diffusion). Yes, over a period of time, the length of which is dependent upon the hydrogeologic characteristics of the formation into which one is injecting, the pressure in the area might build up but it still will be the highest at the point of injection and then dissipate as it radiates out into the vastness of the surrounding formation. (JB: Main-1)

    - This concept is part of standard UIC program principles, which assume that the pressure is highest at the point of injection and declines as flow moves away from the disposal interval.

7. Petroleum engineering methods focus on an existing pressure within a vast area (40-160 acres based upon allowable well spacing) that "pushes" the product (gas or liquid) into a well and as product is removed the pressure will dissipate over time. An injection well operates in the reverse with the highest pressure at the well that dissipates as the pore pressure radiates out form the well. See Basic Mechanism of Injection Induced Seismicity – comments 3 and 4. (JB: Main-10)

    - Petroleum engineering methods are applicable to both withdrawal and injection of fluids into a subsurface reservoir.

INJECTION VOLUME

Related Comments:

1. Another important factor contributing to injection induced seismicity, besides the pore pressure increase from disposal operations, a stressed fault and a pathway for communication of the pressure increase, is the actual volume of fluid injected. For

example, as previously mentioned, high fluid pressures can hydraulic fracture intact rock and at the same time induce small earthquakes. However, even if the fluid pressures used in hydraulic fracturing are high, if the volume is small, the resulting induced events are also typically small. Only if the volumes of fluid injected also become large does it appear that the potential for inducing large magnitude earthquakes also increases [McGarr, 2014]. (CN: Main-3a)

- Injected volume is not a direct part of the three fundamentals, but plays into the change in pressure along with a number of other factors.

2. Although it is indeed true that most existing models used to explain the fundamental mechanism of injection induced seismicity focus on the net pore pressure increase associated with disposal operations, another key contributing factor to the potential for induced seismicity is the volume of fluid injected. This factor also seems to strongly influence the maximum magnitude of the induced earthquake [McGarr, 2014]. The reason for this correlation may be that increasing volumes of fluid allow the pressure effects from well operations to extend farther from the injection well and thus increase the potential that the pressure front will encounter more and larger stressed faults that are close to failure, or that the increased volume allows a larger section of a stressed fault to be brought closer to failure, resulting in a larger earthquake once rupture initiates. Regardless, in providing practical approaches to manage and minimize the potential for injection induced seismicity, it would seem prudent, based on a number of case histories, that the volume of fluid injected, as well as injection pressures and changes in transmissivity also be consider an important factor. (CN: Main-6)

- Injected volume is not a direct part of the three fundamentals but plays into the change in pressure along with a number of other factors, such as transmissibility.

PETROLEUM ENGINEERING APPROACHES

1. APPENDIX D, Figure 9 The comparison of cumulative seismicity to the Hall Integral needs a better defined purpose, and the challenges sound like challenges associated with any seismic monitoring, not necessarily related to the Hall Integral. I am not sure if the example plot is supposed to demonstrate an example of the seismicity and the Hall integral showing a correlation, but it does not do so convincingly. Perhaps if seismicity rate were plotted instead, or if the plot was done as Hall Integral vs. cumulative seismicity, then changes in slope would be easier to see. (HS: App. D-2)

- Details about the Hall Integral are covered in the pages prior to the figure cited. As can be seen, changes in slope are provided by the derivative function. An upward increase in slope indicates decreased injectivity capabilities, while a decrease indicates enhanced injectivity. The challenges listed for the tandem plot are only related to seismic monitoring, as the others had previously been listed.

2. It is the pore pressure that radiates out from a well that interacts with the well. Yes there is a potential that the liquid may reach a fault but the liquid does not grease the existing fault and cause it to slip. The pore pressure disrupts the insitu stress field that is holding the fault together and causes it to slip. (JB: Main-11)

a. The statement regarding "unknown distance" is critical when considering how far the pore pressure will travel. And as it travels, the pore pressure is dissipated, so knowing the distance and perturbation of pore pressure is important. Note that understanding the perturbation of the pore pressure requires very specific data that is rarely known and has to be estimated and sophisticated modeling that is very expensive ($50-150,000/well) (JB: Main-11a)

    - The UIC program routinely deals with these issues in a cost-effective manner, as noted in APPENDIX I and elsewhere, and very little sophisticated modeling is required.

3. Report Findings: Fourth bullet – It needs to be recognized that while a petroleum engineering approach can provide useful information, such approaches can be very time consuming and that there are various factors that can impact the accuracy of the outcomes from such. (ES: Main-19a)

    - Petroleum engineering methods are applicable to both withdrawal and injection of fluids into a subsurface reservoir. The methods do require accurately reported data, but can be carried out in a reasonably short time frame and provide valuable insight.

4. APPENDIX D, Pressure transient testing for disposal wells This section feels weaker than the others. There is too much emphasis put on the “log-log” plots providing “mathematical pictures”. Log-log plots are not inherently special, and are not required because one is considering a partial differential equation. It useful to plot data in log-log space when both parameters will vary over many orders of magnitude. Furthermore, I cannot determine by the plots shown here why any of these analyses cannot be

performed using excel. Although it would certainly be easier with a more sophisticated tool, it can still be accomplished in excel. (HS: App. D-4)

- The plots recommended are the standard petroleum engineering method. Most of the operational plots were performed using Excel. The falloff test analysis is better done using purpose-built modeling software, primarily to handle the amount of data and to take advantage of built-in routines, which provide more consistent results.

5. D-6 Operational Data Plots and Analysis: It would be useful to have Hall plots for disposal wells where there is no record of induced seismicity for comparative purposes. It may be common for most injection wells to have increased injectivity over time. (ES: App.D-2)

    - Yes, it would be useful. The discussion of Research Needs has been updated to reflect the need for baseline data for comparative purposes.

FLOW PATHS, FRACTURE FLOW, AND FAULT MOVEMENT

Related Comments:

1. The discussion in this line (pg 8 para 2 ln 8-9), and in others in the document refereeing to fracture flow, implies that the formation into which you are injecting has been fractured (creation of cracks or faults in hard rock). This is not always the case and is not the predominant formation type into which water is disposed. Rather the disposal formation is typically a porous sedimentary formation that, through its formation, has interstitial space created by varying particle size and shape, that when packed together creates flow channels (JB: Main-9)

    - The referenced paragraph may have been misread. However, most suspect cases of disposal-induced seismicity are in naturally fractured formations.

2. The statement regarding exceedance of the theoretical friction threshold implies that the injection water lubricates the surfaces between the 2 sides of the fault allowing one side to slip along the other side. As presented in Basic Mechanism of Injection Induced Seismicity – comment 1, the primary mechanism is the disruption of the insitu stresses holding the fault together by pore pressure radiating our from the point of injection. (JB: Main-11)

- The information referred to by the reviewer is taken directly from the Nicholson and Wesson (1990) report.

3. Because reservoir engineering analysis methods use data from one location (the well), they cannot identify flow patterns or directions, and hence cannot determine if injected fluid is traveling toward or away from an identified "fault of concern." (RM: Main-5)

    - It is safe to assume that fluid and pressure from a disposal well travel away from the well. The pressure is highest at the point of injection and declines as flow moves away from the disposal interval. Many things influence the pathways, but using the basic UIC program simple radial flow model coupled with a simple diagram will show that flow will also be towards any faults of concern.

4. Again, improving the quantity, quality, and timeliness of information on injection volumes and pressures reported to regulatory agencies along with increased seismic monitoring for small earthquakes (M1.0 or less) is often much more important to managing the earthquake risk from injection activities, or minimizing the potential for injection induced seismicity, than performing additional reservoir engineering analyses with what in some cases is less-than-ideal or insufficient data. (CN: Main-4 all)
    a. The primary goal is to evaluate the pressure-time histories or pressure buildup associated with volumes of fluid injected to better understand reservoir characteristics and the extent to which assumptions, such as a homogeneous reservoir with radial flow, are appropriate.
    b. Most multidisciplinary studies of injection induced seismicity already perform these basic types of reservoir analyses. Any deviation from radial flow, or any indication of increased transmissivity should be scrutinized as possible evidence for increased flow towards and pressure buildup at potentially adjacent faults, or as possible evidence for the opening of fractures or the occurrence of new faulting.
    c. Conducting more sophisticated reservoir engineering analyses besides these basic reservoir modeling studies can in some cases provide additional insight into reservoir behavior and its response to fluid injection, but without adequate input data, such studies often prove to be ambiguous.

    - EPA agrees with the reviewer on the recommendation to improve quality and timing of injection volumes and pressure reporting, especially when there is a concern for induced seismicity. Most *recent* induced seismicity studies do not appear to take the basic reservoir analysis as a necessary evaluation step, perhaps

because petroleum engineers are not the intended audience. Using available UIC program data should be a step in any decision making process.

5. The discussion related to "Future research is needed to explore the correlation between disposal well operational behavior and earthquake events. The research should consider interaction between offset disposal wells on the operational plot characteristics along with area geology (flow geometry related to karstic vs. fractured carbonate)" is very problematic that this would tend to imply to the reader that simple analytic tools can be used to evaluate correlation between the disposal well operational behavior and earthquake events. From a practical view, this is simply not the case and analytic models can not represent the complex physics of the problem….. (KN: Main-14)

    - The purpose of the report was to provide practical tools to the UIC program manager. However, this section has been reworded to more clearly present the intended results, providing additional tools to evaluate induced seismicity.

6. Second, in order to determine whether a fault is optimally oriented to the stress field, the frictional strength of the fault must be assumed. The main paper on this issue cited in this document (Holland 2013), assumed that faults have a frictional strength of 0.6 (this is never stated clearly, but the Hurd and Zoback (2012) paper that Holland references does assume this). It should be made clear that this, in many cases is a complete assumption. Townend and Zoback (2000) demonstrate that some mid-continent faults have friction values close to 0.6, but this should not be assumed in all cases. Although the coefficient of friction of bare rock surfaces is typically this high, faults often have granular gouge layers (from abrasion) that are rich in clays, and have a coefficient of friction closer to 0.3-0.4. Hurd and Zoback (2012) argue that faults in the midcontinent do not have gouge zones, but at least through my own personal experience in the field, I would say that is not usually the case. The presence of clays and weakening of faults changes the range of angles a fault can be from the maximum stress direction and still slip. For instance, the San Andreas fault is oriented almost 90 degrees from the maximum horizontal stress, meaning that it should essentially be pinned (Zoback et al. 1987). Although this is an extreme example, it highlights the uncertainty involved in assigning "faults of interest" based on orientation of the fault to the remote stress field. To highlight this point, I will mention that Holland (2013) suggests that faults in Oklahoma that are oriented east-west are unlikely to host earthquakes, despite the fact that a M5 earthquake occurred on an east-west striking fault as part of the 2011 Prague sequence (Keranen et al. 2013). Although this earthquake may have been pushed to failure by other nearby faults at orientations that would classify them as "faults of interest", the

complexity of fault interaction suggests that limiting the scope of investigation to faults at a certain angle may be problematic. A full characterization of all faults in the vicinity of a well seems more appropriate. (HS: Main-1b)

- Stress field calculations etc., are complex and problematic. Realistically, most faults of concern are identified only after they cause felt seismicity. In contrast, many of the original oil discoveries were found in reservoirs with structural traps, usually involving sealing faults (or the oil would have leaked off). Given many decades of oil exploitation with no measured fault movement at the aforementioned locations, let alone significant movement, concern for all faults would be inappropriate.

7. The other consideration that could be addressed more specifically in this document is that absolute stress levels on faults at any time is unknown, so it is never clear what pressures will be the "tipping point" that causes failure. Time-dependent fault processes, specifically time-dependent frictional properties, should be addressed more in the future as well. Although this is an area of active research, this document would be remiss if it did not at least mention that understanding the processes that involve fault failure is ongoing. For instance, fluid pressure pushes faults towards failure through reduction of effective normal stress, but at the same time make the fault more likely to fail in aseismic slip (Das and Zoback, 2011; Scholz 2002). Aseismic slip on faults can trigger seismic slip further away along the same fault, and this kind of more complex interaction may make spatial interpretation of induced seismicity more difficult. (HS: Main-1c)

    - The key aspects relevant to the intended audience are covered under 0, Rock Mechanics. The next to last bullet covers additional research topics, including those mentioned above.

Report Recommendations

In response to several reviewers' recommendations, a new section, Report/End Product Task Results, was added to the report to clarify where each task result may be found.

As discussed previously, development of a formal risk assessment is outside the Scope of this report as is research, other than a compilation of recommended practical research that fits UIC program needs.

While not in one of the above categories, the additional reviewer recommendations below were considered already sufficiently covered in the report.

Related Comments:

1. Injection Induced Seismicity Project Objectives: It is suggested that the wording of this be changed to – What parameters are most relevant for the assessment of potential injection-induced seismicity? It is believed that this should be considered a risk assessment exercise. (ES: Main-4)
2. Working Group Approach: While it is understood that it would be a considerable task, it would have been useful to study disposal wells in area where no seismic activity has occurred to try to define what differences may exist with those areas where such activity has occurred. It should be noted that the Stanford Center for Induced and Triggered Seismicity is working on developing a detailed stress map of Oklahoma that will be useful to future seismicity assessments there. (ES: Main-5)
3. The Report goes into depth on describing petroleum engineering characterizations (fluid flow, effects of strata permeability and continuity on well performance), seismology (earthquakes and seismic monitoring), and injection operations (decisions on fluid pressures, volumes, and tests) but fails to pull that knowledge together into concrete technical recommendations for "minimizing and managing potential impacts" of IS (per the Report title). The Executive Summary, page ES-2, states "This report is not a guidance document and does not provide specific procedures, but does provide the UIC Director with considerations for addressing induced seismicity on a site specific basis…" This appears to be a failed opportunity to recommend some specific technical steps that could be taken to "minimize and manage potential impacts." The reason stated in the Report for this generality (page 26) is "The site assessment considerations are intended to guide the Director in selecting operational, monitoring, and management approaches that are appropriate to address induced seismicity issues." I expected the Report to recommend such approaches. If specific technical recommendations cannot be given or are not appropriate (e.g. because of the many variables that can affect induced seismicity at individual sites), the reasons should be stated. (RM: Main-4)
4. The "Technical Recommendations…" document in APPENDIX A says that output of the study should include "Recommended measurement or monitoring techniques for higher risk areas." These measurement or monitoring techniques are described in general terms such as injection well operational characteristics, or seismic monitoring arrays, for any well where induced seismicity is a concern. No special recommendations are given for "higher risk areas." (RM: Main-10)
5. Refine for

a. C-6 Basic Seismology: It should be noted that the surface shaking associated with seismic waves is also a function of the hardness of the rock near the surface. (ES: App. C-3)

6. Petroleum Engineering Applications for Evaluating Induced Seismicity (KN: Main-7 all)
    a. The section "Possible Causes of Induced Seismicity" (p. 10) could be readily edited to provide broad overview of other factors that may be present in combination with disposal operations. The report would be strengthened by clearly summarizing the range of factors the UIC regulators may wish to explore if unexpected seismicity is encountered in a specific area. Such a listing could be done in brief summary form, and highlight the important natural and anthropogenic triggers that can perturb the subsurface stress regimes in proximity to faults. These include:
    b. Identification of the natural tectonic stress / strain dynamic behavior in area of concern
    c. Identification/location of natural (dynamic) sources that could lead to subsurface stress perturbations; including naturally-occurring "overburden" formation density changes under drought or excessive rainfall conditions
    d. Identification/location of natural geothermal "hot-spots" in the area of concern. etc.
    e. Identification/location of anthropogenic sources that could lead to subsurface stress perturbations (injection wells; production wells; mining / blasting operations, geothermal operations, reservoir impoundment / dam construction, etc.)
    f. Identification / location of potential synergies between natural and dynamic sources, for example, such as aquifer / groundwater withdrawals for irrigation and human consumption purposes, in combination with drought conditions
7. The pressure data collected by the well operators is a key component to identifying where induced seismicity may soon occur. I want to make a point of mentioning that the quality and availability of these data can vary widely. In the same vein, the case of Youngstown, Ohio is highlighted as one in which the well operators provided daily pumping records. Most of the case studies mentioned here also have fairly detailed pumping records. To my knowledge, daily records are not required to be reported anywhere right now. Furthermore, even on the state level, the ease of accessing injection information can be quite different. The report highlights the Texas Railroad Commission as one of the state agencies that runs a database with this information, however, Texas has one of the better sites. Furthermore, some states, like Oklahoma, have limited online information, or websites that make the data difficult to access except on an individual well by well basis.

As this report emphasizes, monthly (or more frequent) pumping records are essential for seeing any changes in reservoir pressure or flow rate that may indicate that faulting or fracture is taking place within the reservoir. Daily records would be better but are not usually made available. Combining daily pumping records with continuous, well-located seismicity would be a powerful tool for monitoring and mitigating induced seismicity. But relying on what is currently reported is going to mean coming up with a way to make reporting in some states more reliable and easier to access. (HS: App. D-1)

HISTORIC SEISMICITY

Related Comments:

1. The discussion of how to use historic seismic events as an indicator of potential induced seismicity can be argued from both sides. Presence of historic seismicity can be an indicator of an active seismic region or it can be argued that the historic seismic events have released the stored energy thus the potential for a critically stressed fault (See Basic Mechanism of Injection Induced Seismicity – comment 3) to be located in the area is low. Likewise if there is no historic seismicity, it can be argued that the area is dormant or you can argue that the area is just storing up energy creating critically stressed faults that are waiting to be triggered. (JB: ES-6)

    - USGS seismic hazard maps are based on specifics from the historic seismic record (especially surface acceleration). Locating disposal wells in areas of historical seismic activity warrants some additional caution. Likewise, permitting disposal in areas with no historic seismicity, but known faulting, warrants caution. The document focuses on practical approaches for dealing with possible induced seismicity, and the use of existing historical data is certainly an indicator of the potential for inducing seismicity and should not be ignored.

2. Page 15, N. Texas Area Suggest revising the sentence "Since the two wells were shut-in the frequency of seismic events in the immediate focus area has substantially decreased" as this is contradictory to information contained in the Janská, E., Eisner, L. 2012 publication that that suggests seismicity continued for an extended time period in proximity to one well after shut-in (when considering the DFW airport measurements). (KN: Main-10)

- The sections have been rewritten for clarity. However, the statement is correct for the published seismic events. ComCat [49] includes few if any of the events in the cited publication. The publication cited did not include a list of seismic events, only the mapped relocations and the technique by which the events were identified from previously uncounted background events.

3. Preliminary Assessment of Existing or New Oil and Gas Waste Disposal Wells: Second bullet – It would be useful to suggest over what time frame increases in frequency or magnitude should be reviewed. It is suggested that this should be performed covering a period of at least one year prior to the assessment. (ES: Main-15)

    - Given the wide range of conditions the decision model is designed to consider, too much specificity reduces the applicability across the nation.

4. The USGS historical seismicity map along with other regional historical seismicity data is all regional and can help understand regional seismicity but it is not useful when zeroing in on an injection well location whose area of potential impact smaller than the error ellipses for historic seismic events that could led to a false positive determination (JB: App. B-2)

    - The decision model is designed for the complete range of conditions, from new permits to existing wells in areas where seismicity occurs. Regional seismicity data is needed for the initial assessment of basement stresses, as described in the report. It can therefore serve as a tool for evaluating local stress conditions. The report also cites use of all available seismicity sources including more local state data. Additionally, for high volume, high pressure disposal wells or for long-term low volume or wells on vacuum, the area of pressure impact can be far-reaching, especially in fractured formations. See Appendices I and J.

Stop Light aka Traffic Light

A number of reviewers focused on additional requirements including 'stop light' requirements, risk management or formal risk assessment, and continued research while continuing to inject. These suggested requirements are a matter of policy and outside the scope of the document.

[49] ComCat is the current USGS earthquake catalog.

While the report does not use the 'stop light' term, the concept is covered in the decision model as part of permitting conditions or contingencies under the section on Management Approaches. Many of the approaches in the 'stop light' methodology, developed by the geothermal industry, are discussed as permitting contingency options, without using 'stop light' as a specific term. The paper that introduced the concept is included in the bibliography in APPENDIX K (Majer et al., 2011).

Related Comments:

1. Management Approach: Third bullet – A stop-light approach such as has been suggested by various authors and organizations such as the National Academy of Sciences should be endorsed as a practical tool for regulatory agencies to follow with the particulars left up to the agencies to reflect their particular geology and concerns. (ES: Main-18)