White Paper II Summarizing a Special Session on Induced Seismicity

This special technology transfer session for seismologists, regulators, and other stakeholders entitled *"Assessing & Managing Risk of Induced Seismicity by Injection"* was a part of the GWREF Spotlight Series.

The Ground Water Research & Education Foundation (GWREF) is a not-for-profit 501(c) 3 corporation dedicated to promoting research and education related to the protection of ground water.

Our mission is to promote and conduct research, education, and outreach, in the areas of development and application of technical systems, pollution prevention efforts related to ground water protection, underground injection technology, and watershed conservation and protection.

The foundation is comprised of a board made up of volunteers from government, institutes of higher education, and the public appointed through the Ground Water Protection Council.

November 2013

White Paper II Summarizing a Special Session on Induced Seismicity[1]

Chapter 1 - Introduction

1.1 Background

The topic of induced seismicity, or earthquakes caused by human activities, and in particular seismicity associated with hydraulic fracturing and disposal wells, has been the source of heightened interest and controversy over the past several years. To help disseminate factual information on the subject, the Ground Water Protection Council (GWPC) and its research arm, the Ground Water Research and Education Foundation (GWREF), decided to include sessions on induced seismicity in two of the organization's 2013 conferences.

GWPC held its 2013 Underground Injection Control Conference in Sarasota, Florida on January 22-24, 2013. On January 23, the conference included a special session entitled "Assessing & Managing Risk of Induced Seismicity by Underground Injection". A white paper summarizing the presentations and discussions that were part of the session was prepared following that meeting. It can be found on the GWPC website.

GWPC held its 2013 Annual Forum in St. Louis, Missouri on September 23-25, 2013. Building on the success of the induced seismicity session in January, the conference included a special half-day session on September 23 entitled "Assessing & Managing Risk of Induced Seismicity by Underground Injection".

1.2 The Special Session

The January induced seismicity session included more speakers and covered much more material than did the September session. Much of the material covered in the September session described specialized research findings or provided an update to state regulatory topics that had been discussed at the earlier session.

The September session included 12 presentations separated into three groups: "Studies: Researchers Presenting Findings and Research Strategies"; "Industry: State of the Art Technology Used to Limit Risk"; and "Regulatory". Lori Wrotenbery of the Oklahoma Corporation Commission chaired the session.

[1] The white paper was prepared for GWPC by John Veil of Veil Environmental, LLC.

1.3 The White Paper

This white paper summarizes the information that was discussed during the special session. It is not intended to be a complete and detailed report on the subject of induced seismicity, but is generally limited to the information actually presented during the twelve presentations and any associated discussion during the question and answer periods. Unlike the first white paper, which covered the broader range of topics that were discussed during the January session, white paper II is shorter and more focused on a few subjects that were presented. Considerably less general background information on seismicity, induced or natural, was presented in the September session; therefore, not as much background is included in white paper II either.

A detailed technical report on induced seismicity was released by the National Research Council of the National Academy of Sciences (NAS) in 2012. That report contains much broader and in-depth coverage of induced seismicity and was written collaboratively by experts in the field. The NAS report was referenced frequently during the January session, but was not mentioned much during the September meeting. The earlier white paper included an entire chapter on the NAS report, since many of the presenters referenced that report. In this second white paper, the NAS report is not discussed in detail.

Readers are encouraged to read the first white paper for a basic overview of the subject or to read the NAS report[2] for an in-depth look at the subject.

Much of the material presented during the September session is highly technical and esoteric. That information is very useful to specialists and practitioners. But in order to explain the importance of induced seismicity and the issues surrounding it to a wider audience, white paper II, like the first white paper, is written in a style and at a level for a broader non-technical audience.

Several of the speakers in the session agreed to let the GWPC post copies of their presentations on the GWPC website. Where those presentations are available, they are directly linked to references in this white paper. For those other presentations whose authors did not authorize the GWPC to post the slides, relevant information is summarized, and reference is made to their names – readers can contact those authors directly for additional information. Most of the state regulatory speakers did not use Powerpoint slides. Their remarks are summarized in Chapter 7.

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[2] National Academy of Sciences, 2012, "Induced Seismicity Potential in Energy Technologies," prepared by an NAS Committee on Induced Seismicity Potential in Energy Technologies, published by the National Academies Press, Washington, DC, 300 pp. The report can be ordered in hard copy or downloaded in .pdf format at http://www.nap.edu/catalog.php?record_id=13355.

Chapter 2 – Seismicity – Natural and Induced

This chapter provides a brief overview of seismicity, its causes, and the range of intensity and impact caused by earthquakes. The first white paper covers these subjects in more detail.

2.1 What Is Seismicity?

According to the U.S. Geological Survey's Earthquake Glossary (http://earthquake.usgs.gov/learn/glossary/), "seismicity" refers to the geographic and historical distribution of earthquakes. Throughout the rest of white paper II, the terms seismic event and earthquake are used interchangeably.

Austin Holland of the Oklahoma Geological Survey presented some background on earthquakes. He noted that an earthquake is caused when two bodies of rock slide past each other (known as a "rupture"). Energy in the form of seismic waves is radiated out from the rupture in all directions. Seismic waves travel through the earth to seismic stations that help locate and determine the size of the earthquake (magnitude).

Many earthquakes occur every day from natural forces within the earth. Most are far too small to be felt by humans at the surface, but seismic instruments can detect and document many of the small events. These frequent small earthquakes do not cause damage to manmade structures.

Holland reported that most earthquakes, especially large ones, occur at plate boundaries, but not all earthquakes occur there. Earthquake locations cannot always be identified precisely because adequate coverage of seismic monitoring stations in the area of the earthquake is not always possible. Having multiple stations situated reasonably close to the source of the earthquake aids in establishing a more precise location

2.1.1 Magnitude and Intensity of Seismic Events

Seismic events occur with varying degrees of intensity; there are many more small events than larger ones. Holland reported that magnitude is proportional to rupture area and the slippage on the fault.

The scientific community has developed various scales to characterize the strength of individual earthquakes. The most familiar scale to the public for characterizing the magnitude of earthquakes is the Richter scale, developed in the 1930s. A physics-based scale, developed in the 1970s, that also measures the magnitude of earthquakes is called the Moment Magnitude scale. It is commonly used now by the scientific community. Both scales assign numbers to events of different sizes. The numbers represent the amplitude (height) of the seismic waves

measured on a seismograph and run on a logarithmic scale (i.e., the wave amplitude of a 4.0 earthquake is ten times that of a 3.0 earthquake). Holland noted that increasing the magnitude by one unit results in a release of about 32 times as much energy.

If an earthquake is strong enough, the energy released during the event may reach the earth's surface at such a level to cause noticeable shaking. Damage to structures, if any, depends on the amount of energy reaching the surface, the characteristics of the soil, and the structural design and physical condition of the local structures. There is a difference between merely measuring the presence of an earthquake and making an evaluation of its impact at the surface of the earth. To better measure the intensity of earthquakes, scientists developed the Modified Mercalli Intensity (MMI) scale. The MMI uses the perceived effects of a seismic event on the people and structures at the surface to determine its intensity at any given location, providing a map of how the intensity varies in the affected area. The MMI includes 12 levels of seismic event severity, ranging from imperceptible to devastating. The numeric values of the magnitude scales (Richter and Moment Magnitude) as well as the MMI scale increase with the strength of an event, but the values do not match up in an exact linear manner and cannot be directly correlated. For measuring the impact of an earthquake on people and structures, the MMI level is more useful in describing actual local effects and has been used by the U.S. Geological Survey (USGS) in the development of educational materials for the general public.

Figure 1 is based on figures used in the presentation made by Kris Nygaard of ExxonMobil. The figure shows the relationship between the Richter scale and the MMI, and describes the types of surface effects that represent events of different magnitude. Nygaard noted that Figure 1 is based on data collected in California from several data sources. He added that that the U.S. National Earthquake Hazards Reduction Program (NEHRP) has recommended additional measurements of peak ground acceleration be obtained in the Midwest and East regions of the United States so that improved relationships can be developed to better correlate between magnitude and peak ground acceleration for those regions.

2.2 What Is Induced Seismicity?

The NAS report states: "Earthquakes attributable to human activities are called 'induced seismic events' or 'induced earthquakes'." The NAS report further indicated: "Seismicity induced by human activity related to energy technologies is caused by change in pore pressure and/or change in stress taking place in the presence of (1) faults with specific properties and orientations, and (2) a critical state of stress in the rocks. In general, existing faults and fractures are stable (or are not sliding) under the natural horizontal and vertical stresses acting on subsurface rocks. However, the crustal stress in any given area is perpetually in a state in which any stress change, for example through a change in subsurface pore pressure due to

Figure 1 – Comparison of MMI Values and Magnitude Scale

Potential Damage	MMI	Perceived Shaking	Approximate Magnitude*	Description of Intensity Level
None	I	Not Felt	1.0 - 3.0	Not felt except by a very few under especially favorable conditions.
	II	Weak	3.0-3.9	Felt only by a few persons at rest, especially on upper floors of buildings.
	III			Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
	IV	Light	4.0-4.9	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
Very Light	V	Moderate	4.0-4.9	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
Light	VI	Strong	5.0-5.9	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
Moderate	VII	Very Strong	5.0-6.9	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
Moderate/ Heavy	VIII	Severe	6.0-6.9	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
Heavy	IX	Violent	6.0-6.9	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
Very Heavy	X	Extreme	>7.0	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
	XI			Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
	XII			Damage total. Lines of sight and level are distorted. Objects thrown into the air.

*Magnitudes correspond to intensities that are typically observed at locations near the epicenter of earthquakes of these magnitudes.

Source: Presentation by Nygaard

injecting or extracting fluid from a well, may change the stress acting on a nearby fault. This change in stress may result in slip or movement along that fault creating a seismic event."

2.3 What Causes Induced Seismicity?

Holland indicated that the physical causes of induced seismicity included either or both an increase in shear stress (e.g., mass changes, permeability barriers, thermal changes) or an

increase in pore pressure (e.g., fluid injection). He further noted that earthquakes can be caused naturally by:

- The passage of seismic waves
- Remote triggering
- Local stress changes from previous earthquakes
- Natural fluid movement
- Hydrologic loads.

Nygaard listed several human activities that can induce seismicity:

- Geothermal energy
- Carbon capture and storage
- Mining
- Dam/reservoir impoundment
- Waste water disposal wells
- Oil and gas injection/extraction
- Hydraulic fracturing.

Evelyn Roeloffs of the U.S. Geological Survey (USGS) suggested that the criteria for determining if an earthquake is natural or induced (as suggested by Davis and Frohlich in 1993) should be re-examined. Those criteria included several questions:

1. Are they the first known earthquakes of this type in the region?
2. Clear time correlation between injection and seismic activity?
3a. Are epicenters near the well(s)?
3b. Are some earthquake depths at or near injection depths?
3c. If some earthquakes occur away from wells, are there known geologic structures that may channel fluid flow to sites of earthquakes?
4a. Are bottom-hole fluid-pressure changes sufficient to cause fault slip?
4b. Are fluid-pressure changes sufficient to encourage fault slip at hypocentral locations?

These questions roughly mimic the physical process of an induced earthquake and are phrased in such a way as to support an earthquake being induced if all answers are yes. If the seismic rate increases following installation of an injection well nearby, this may be evidence of induced seismicity. In addition, the earthquakes need to be spatially and temporally co-located with injection as pore pressure changes are highest near the wellbore and drop off exponentially with distance.

Chapter 3 – Seismic Monitoring and Earthquake Detection

As noted previously, very small earthquakes occur daily in many locations. If the earthquakes occur close to a seismic monitoring station, they may be detected. As the distance between the earthquake location and the seismic station increases, it becomes less likely that very small earthquakes will be monitored. This chapter describes examples of monitoring stations and networks and how well the collected data reflect actual conditions.

3.1 More Closely Spaced Monitoring Networks Yield More Accurate Data

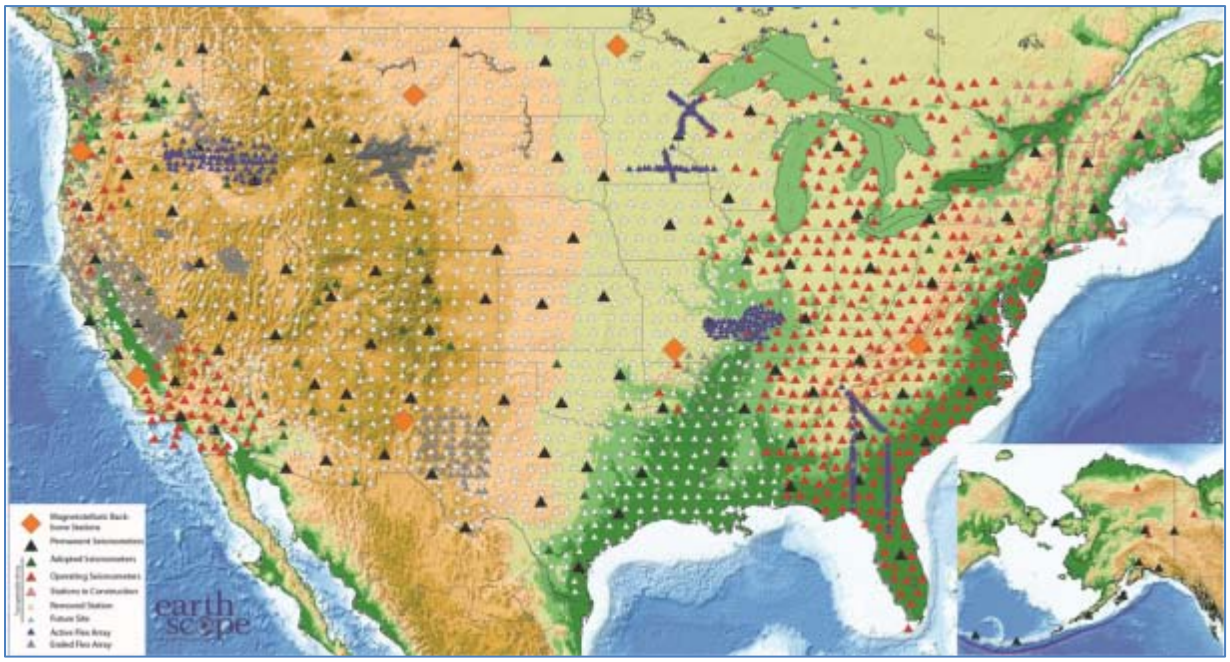
Roeloffs noted that the spacing of the national seismic monitoring network does not allow detection of most earthquakes of magnitude lower than 2.5. The location of the earthquake epicenter may have uncertainties of several kilometers in certain areas of the nation. Furthermore, uncertainties in the depth of the earthquake can be even larger if no seismometers are located on the surface within the range of the depth of the earthquake.

She reported that the seismic network installed at the Bureau of Reclamation's Paradox Valley facility operated from 1991-2011. The injection well facility at Paradox Valley has been operating since 1995 and is a documented case of injection-induced seismicity. As a result of the risk of induced seismicity at this site, the Bureau installed a dense network of seismometers to accurately locate small magnitude earthquakes. This dense network was able to detect and locate earthquakes as small as magnitude -1.5. As a result, a much more detailed picture of earthquake occurrence and magnitudes was possible at that location. Roeloffs further noted that if monitoring at Paradox Valley had relied only on data from the national seismic network, there would have been a long delay between start of injection and the first earthquake detected by the national seismic monitoring network.

Roeloffs also cited a suspected case of induced seismicity in the Raton Basin, Colorado. Since injection began in the basin in 1994, the seismic rate has experienced a drastic increase in the number of >M4.0 earthquakes. However, many small magnitude earthquakes were missed or were poorly located as a result of no local seismic monitoring network. She noted that during the period when the the EarthScope Transportable Array (TA), a densely-spaced seismometer network that is being moved periodically across the United States, was located in the Raton Basin region, it detected a previously unknown fault in the area of the injection wells that accounted for many additional earthquakes.

Figure 2 (taken from the presentation by Nicholas van der Elst) shows the locations of the TA stations during July 2013 as red triangles. Previous locations for the TA are shown in white triangles.

Figure 2 – Map of Current and Previous TA Seismic Stations – as of July 2013



Source: www.earthscope.org, as included in Van der Elst's presentation

3.2 USGS 2008 Earthquake Seismic Hazard Maps

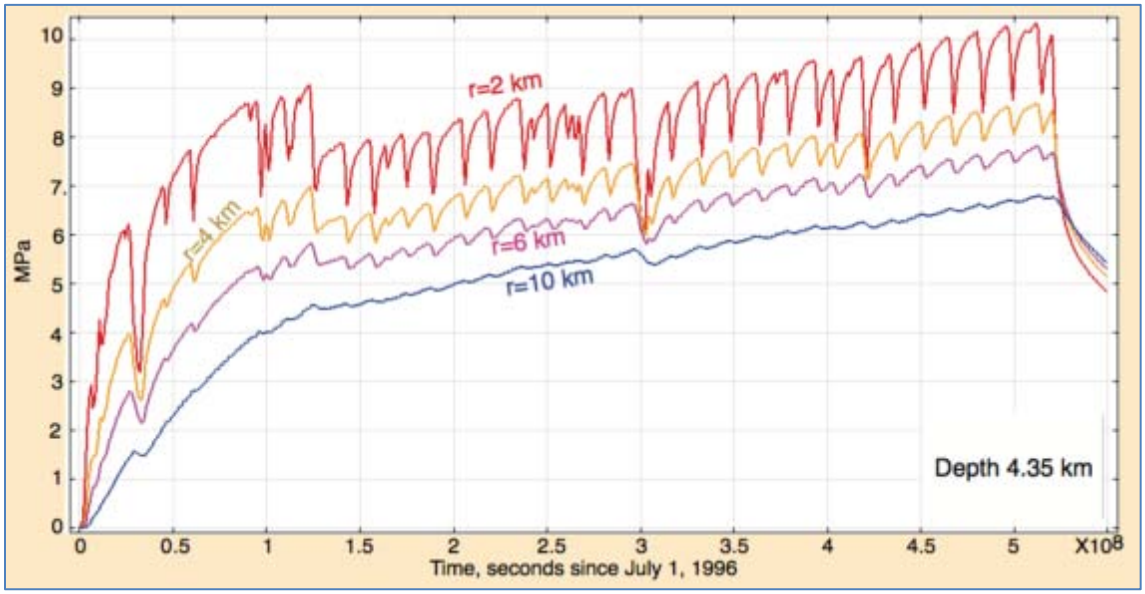
The USGS website (http://earthquake.usgs.gov/hazards/products/) provides a link to the National Seismic Hazard Maps, the most recent of which is dated 2008. The website states: "The maps display earthquake ground motions for various probability levels across the United States and are applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy. This update of the maps incorporates new findings on earthquake ground shaking, faults, seismicity, and geodesy. The resulting maps are derived from seismic hazard curves calculated on a grid of sites across the United States that describe the frequency of exceeding a set of ground motions."

Roeloffs reported that the USGS 2008 hazard map is currently being updated. Work by her USGS colleagues J. Rubinstein, W. Ellsworth, and A. Llenos shows that induced events are frequent enough and, recently, large enough, to increase seismic hazard. She indicated that induced seismicity is increasing the seismic hazard for the United States but is not included in 2008 map. She also explained why some previously induced earthquakes were removed from the map – they were transient activities that are no longer active or ongoing activities believed to pose low hazard risk. Roeleffs noted that the next update to the hazard maps, to be available in 2014, may include induced earthquake contributions. As a result, she suggested that building codes may be strengthened, and insurance rates could rise.

3.3 USGS Modeling Work

Roeloffs described a coupled flow-stress model that she and her colleagues at USGS were developing to further estimate induced pressures and stresses at Paradox Valley. She reported that wellhead pressure rises over time with low permeability barriers located at different radial distances from the injection well. The results found that stress concentrations develop above and below the depth of the injection horizon. Shear stresses extend radially out to nearly 28 km from the well. Figure 3 shows that injection interval pressure variations become less pronounced as the distance from well increases. The importance of this fact is that pore pressure changes at distance from an injection well are less sensitive to injection activities such as turning down wellhead pressure. Therefore, induced earthquakes may persistent at distance from an injection well even months after shutoff.

Figure 3 – Pressure at Different Distances from the Injection Well



Source: Roeloffs presentation

3.4 More Data Are Needed

All of the speakers who are trained as seismologists echoed the theme that an insufficient density of seismic monitoring stations prevents seismologists from detecting many earthquakes. It also hinders their ability to identify locations of faults that are not previously known. When the TA was located in different parts of the country, it helped generate much more information on local earthquakes.

Roeloffs concluded that research progress requires better seismic networks around injection wells. She added that modeling simulations require more detailed pressure and flow records as well as pre-injection pressures.

Nygaard commented that the NEHRP has recommended that additional measurements of peak ground acceleration be obtained in the Midwest and East regions of the United States so that improved relationships can be developed to better correlate between magnitude and peak ground acceleration/ground shaking for those regions to obtain better definition of the hazards based on ground shaking. He noted that ground shaking is the important element to consider when considering the hazard and the risk management and mitigation protocols.

Chapter 4 – Examples of Induced Seismicity

4.1 Examples Discussed during the January Session

The January session provided detailed discussions of several well-known earthquake sites. These included examples in the areas listed below. Readers are referred to the first white paper for more details on these examples.

- Basel, Switzerland - a magnitude 3.4 earthquake associated with injection of water for an enhanced geothermal project in 2006.
- The Geysers geothermal project in California, which has caused 20-30 magnitude 3 felt seismic events and a few magnitude 4 events per year since 2005. The largest event recorded was magnitude 4.6.
- Rangely oil field in northwestern Colorado. Oil production started many decades ago and was later augmented by water flooding operations beginning in 1957. Within a few years, the formation pore pressure rose to a level that triggered seismic events up to a magnitude 3.4. The area of injection was experiencing about 50 minor earthquakes per day. The oil company operating the field agreed to let the USGS conduct an experiment to determine whether they could turn earthquakes off and on by injecting or withdrawing water from the formation. The researchers were successful in this experiment.
- Eola Field in Oklahoma – some published reports have suggested that hydraulic fracturing may have contributed to induced seismicity with magnitudes up to 2.9.
- Blackpool, United Kingdom - Cuadrilla Resources began drilling and completing some of the first shale gas wells in the UK in 2011 in the Bowland Shale. The hydraulic fracturing triggered earthquakes of 2.3 and 1.5 magnitude. The 2.3 earthquake was felt widely by residents, which created a great deal of media attention. Cuadrilla suspended drilling and fracturing while it undertook an extensive study.
- Prague, Oklahoma – This area experienced a magnitude 5.7 earthquake in 2011. Three UIC disposal wells are located within a mile of the earthquake location.
- Guy-Greenbrier fault -- Following injection of produced water and flowback water from shale gas production into several disposal wells, a previously unknown fault, the Guy-Greenbrier fault, experienced over 1,300 earthquakes with magnitudes up to 4.7 that occurred starting in September 2010. However, the vast majority of these events were relatively small in magnitude.
- Youngstown, Ohio – twelve seismic events with magnitude as high as 4.0 occurred near a disposal well.

- Dallas-Ft. Worth airport -- during 2008-2009 a series of earthquakes occurred in this area. The cause was proposed to be a nearby disposal well.
- Braxton County, West Virginia – This area began experiencing small earthquakes in the range of magnitude 2.2 to 3.4 in April 2010 near a disposal well.
- Rocky Mountain Arsenal, Colorado -- The U.S. Army decided to inject liquid waste into a 12,045-foot deep disposal well. Injection began in March 1962. Less than a year after injection began, earthquakes began occurring in the vicinity. Thousands of small earthquakes were recorded near the Arsenal. In 1967, two earthquakes occurred with magnitude of 4.8. In 1968 injection stopped.
- Paradox Valley, Colorado - The U.S. Bureau of Reclamation operates a project to reduce the amount of salt entering the Dolores River and ultimately the Colorado River. They collect naturally occurring seepage of salt brine and dispose of it in part by injection to a deep limestone formation. During 6 years of pre-injection seismic measurement, the Bureau recorded only one earthquake. However, once injection began in July 1996, earthquakes were recorded almost immediately. Minor earthquakes continued through mid-1999, and two magnitude 3.5 events occurred in June and July of 1999. In response to the higher magnitude earthquakes, the Bureau of Reclamation initiated a program to cease injection for 20 days every six months. After experiencing a magnitude 4.3 earthquake in May 2000, they reduced injection to every other month. The largest earthquake since then was a magnitude 3.9 event in January 2013.

4.2 An Example Discussed during the September Session

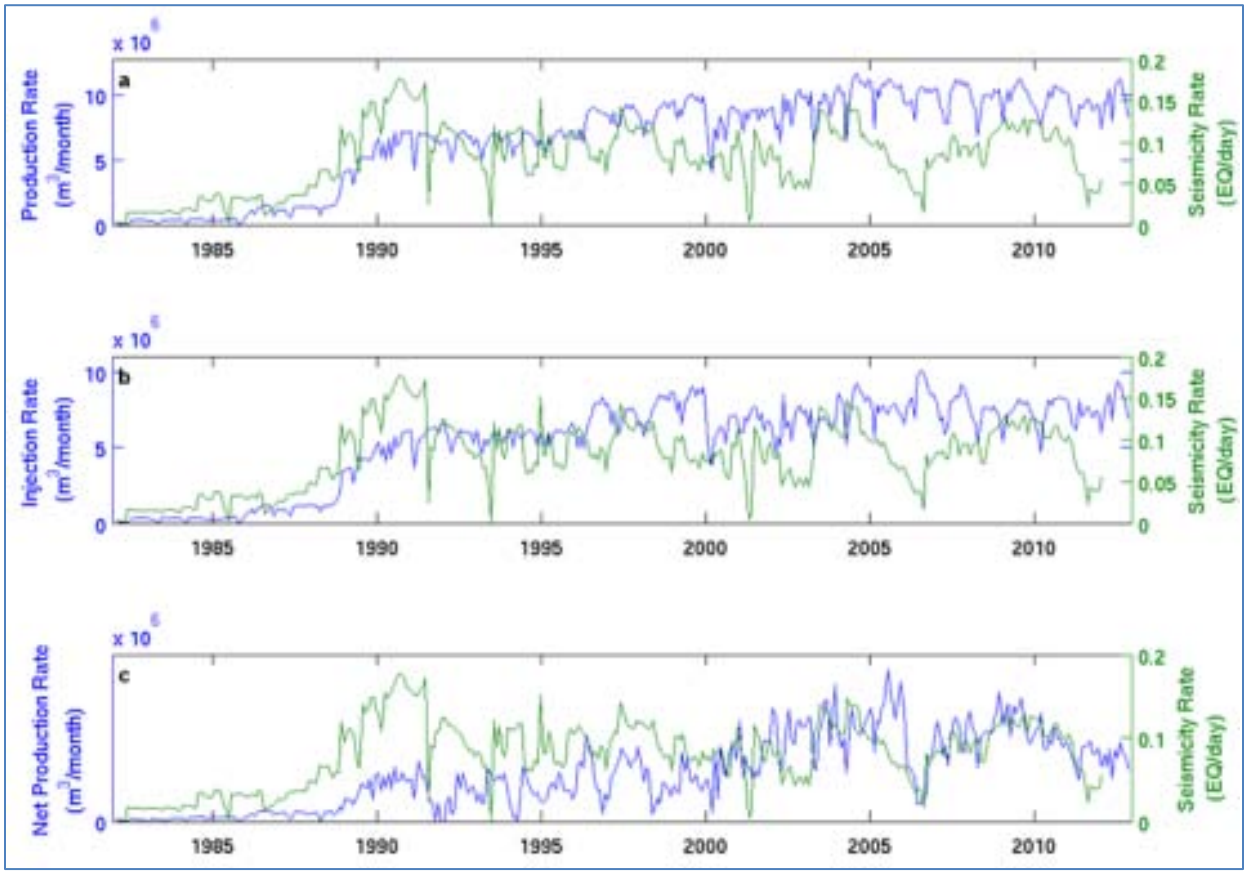
Some of the examples listed above were mentioned briefly in a few of the presentations made in the September session. However, only Lia Lajoie of Fugro Consultants, Inc. described any new detailed case examples. She talked about the Salton Sea and Coso geothermal projects in California that had caused some earthquake activity. Both sites involve geothermal formations that are considered to be “hot, wet rock” – this type of formation does not require hydraulic fracturing.

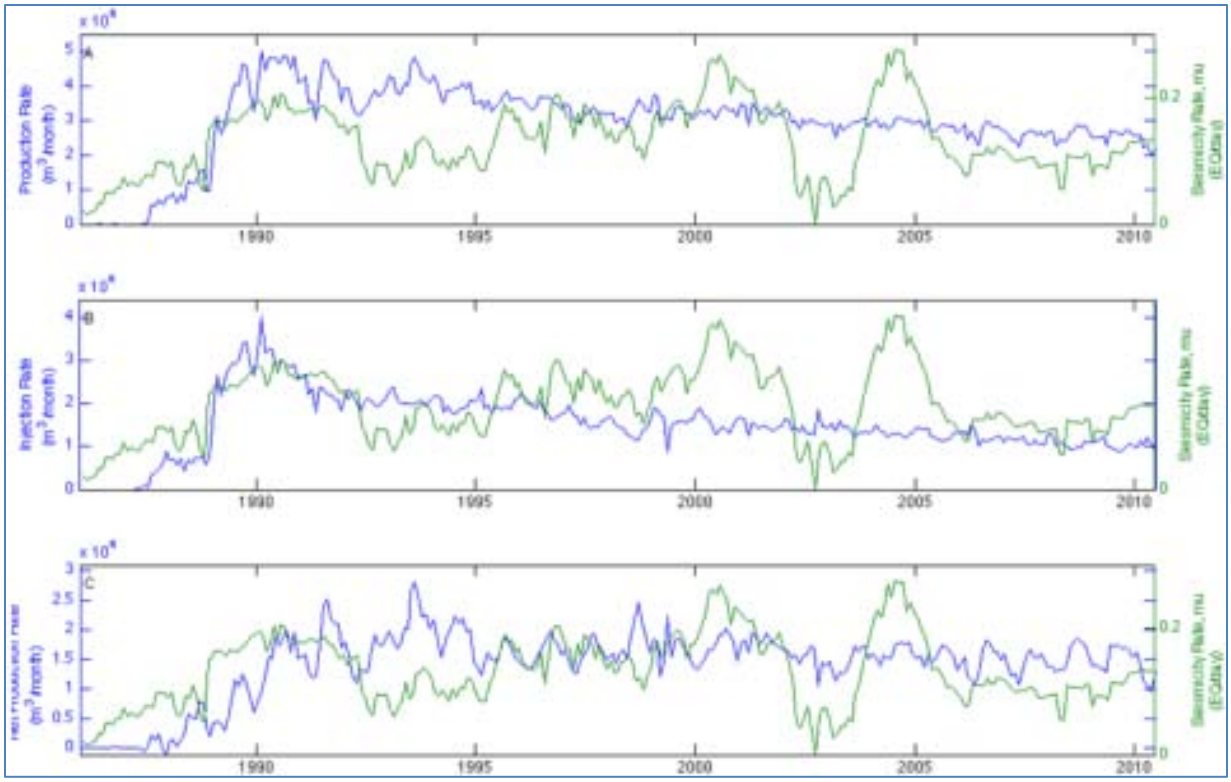
Lajoie employed the ETAS (epidemic-type aftershock sequence) model to look for changes in background seismicity rate at the two sites. ETAS is a model of seismicity based on interacting events that may trigger a cascade of earthquakes. The ETAS model classifies seismicity into two components -- background seismicity and aftershock seismicity. Background earthquakes are those that primarily respond to stresses in the rock mass (or changes therein), and aftershocks, in a simple sense, respond to stresses imparted on the rock mass by the main shocks. Being able to isolate these two components of seismicity allows for comparisons to be made between fluid injection and production rates (which alter the local stress field) and the rate of

earthquakes that are responding most directly to the fluid-induced stress changes (background events). The numerical simulations in the model are quite complex – far beyond the scope of white paper II. Readers are directed to Lajoie's presentation to see the equations and approach she followed.

The results of the modeling for both facilities are shown in Figure 4. Results for the Salton Sea plant are shown in the top box, and for the Coso plant in the bottom box.

Figure 4 – Production, Injection, and Net Production vs. Background Seismicity at the Salton Sea (top) and Coso (bottom) Geothermal Plants





Source: Lajoie presentation

Lajoie concludes that a combination of net production and injection/production information can explain the majority of background seismicity in the geothermal fields, and is a good predictor of seismic response in the short term. The importance of net production volume (which is the difference between production and injection, or the net extraction from a reservoir) suggests that increased pore pressure is not the only factor affecting anthropogenic seismicity rates. Using modeling, Lajoie was able to begin to identify which fluid flux is having the greatest influence on seismicity in a given month. She noted that having more data as well as data of higher quality would be essential to better understand seismicity at these locations.

Chapter 5 – Triggered Earthquakes

A large earthquake sends out seismic waves that move through the earth's crust. In some cases, the seismic waves can trigger other smaller earthquakes as they pass by sites that are already primed for an earthquake. This chapter describes the information that was presented during the meeting relating to triggered earthquakes.

5.1 Conditions that Favor a Triggered Earthquake Response

Holland reported that most of the Earth's upper crust is near failure. This means that even small reductions in effective stress, from passing seismic waves or increased pore pressure, can trigger earthquakes. The increased pore pressure from fluid injection effectively reduces friction on faults.

Nicholas van der Elst of Lamont-Doherty Earth Observatory reported that some earthquakes are set off by passing seismic waves initiating from big, distant earthquakes. They represent a small proportion of all earthquakes, but are not uncommon. The mechanism for triggering an earthquake is not well understood, but the scientific community believes they require critical stresses and are encouraged by high fluid pressure conditions.

Van der Elst talked about how fluids are most likely involved in naturally triggered earthquakes. He noted that triggered earthquakes are observed more often at sites with fluids such as volcanically active areas. He also mentioned that seismic waves have other hydrologic effects such as:

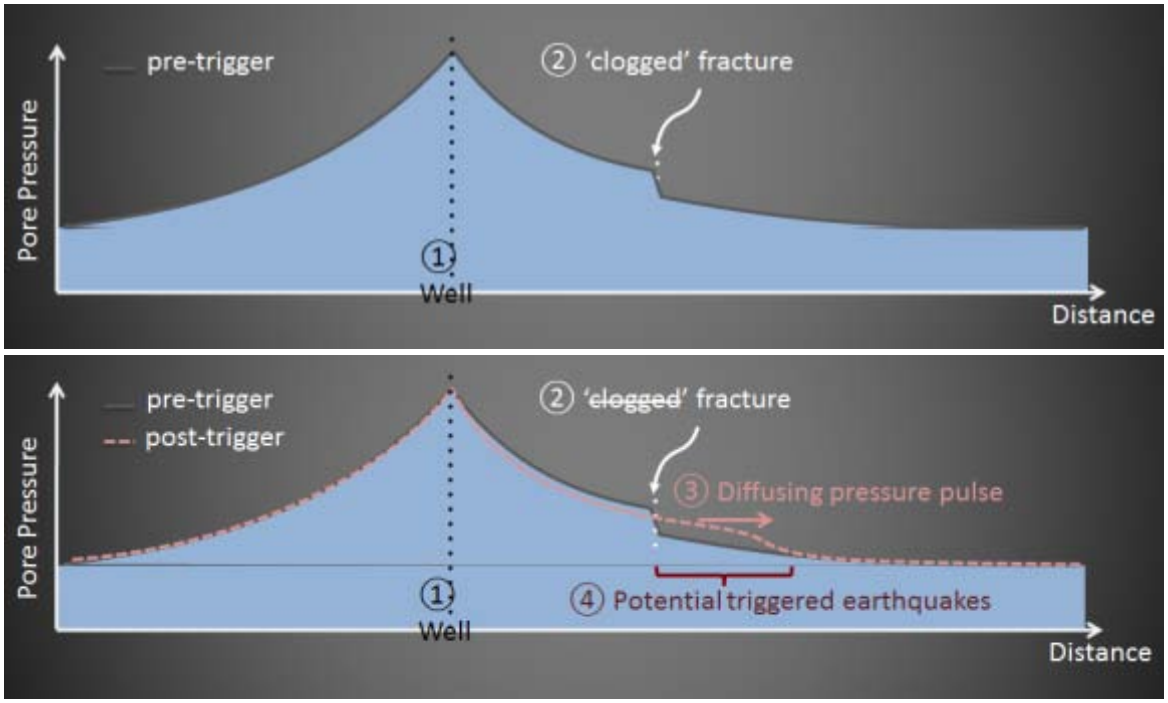
- Mud eruptions
- Stream flow changes
- Well water level changes
- Geyser frequency changes
- Triggered inflation/deflation at volcanoes.

Van de Elst reported that as seismic waves move through a formation, the permeability of the formation increases. He postulates that this is due to unclogging of fractures, and showed examples from the field as well as a laboratory experiment. Figure 5 plots pore pressure vs. distance from the well. The top figure shows the pre-triggered condition. At location 2, a fracture is clogged resulting in higher pore pressure on one side of the fracture. The bottom figure shows how a passing seismic wave can unclog the fracture, diffuse the pressure pulse, and potentially trigger one or more earthquakes.

5.2 Detection of Triggered Earthquakes

According to van der Elst, most seismic networks are not dense enough to catch small triggered earthquakes. Typically only one seismic station is located within 100 km of any point, and he suggests that at least four stations are needed to locate an earthquake.

Figure 5 – Effect of Seismic Pulse on Permeability and Triggered Earthquakes



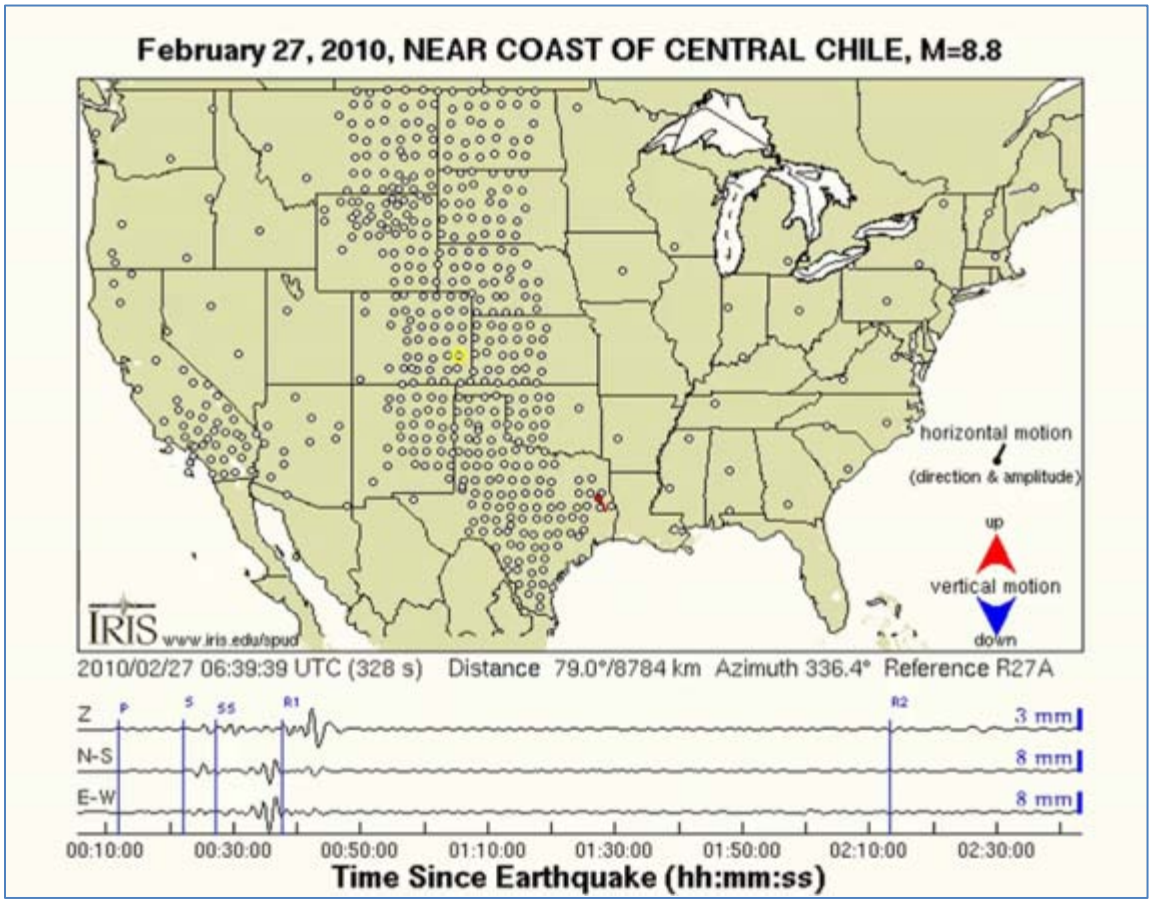
Source: Van der Elst presentation

Van der Elst showed examples of triggered earthquakes that were detected by the TA. A magnitude 8.8 earthquake occurred in Maule, Chile on February 27, 2010. It sent significant seismic waves around the world. At that time, the TA was located in a wide band running from Texas to Montana and North Dakota. Figure 6 is a static version of a video showed by van der Elst. In the video (available for downloading at http://www.iris.edu/spud/gmv/2400 -- choose the 3-component GMV view for the most interesting display), each station (locations shown as small circles) reacts as the seismic waves pass through. Each of the TA stations showed horizontal and vertical movement.

In the absence of the densely spaced TA, the local triggered earthquakes may not have been detected. Even with the TA stations, a matched filter had to be used retrospectively.

Van der Elst described a method for comparing long-term seismic data to identify earthquakes. The matched filter method shows spatial and temporal peaks that define the location and origin time of events too small to be detected by general seismic detection techniques. Earthquakes with identical waveforms must come from the same swarm.

Figure 6 – Locations of TA Stations in February 2010



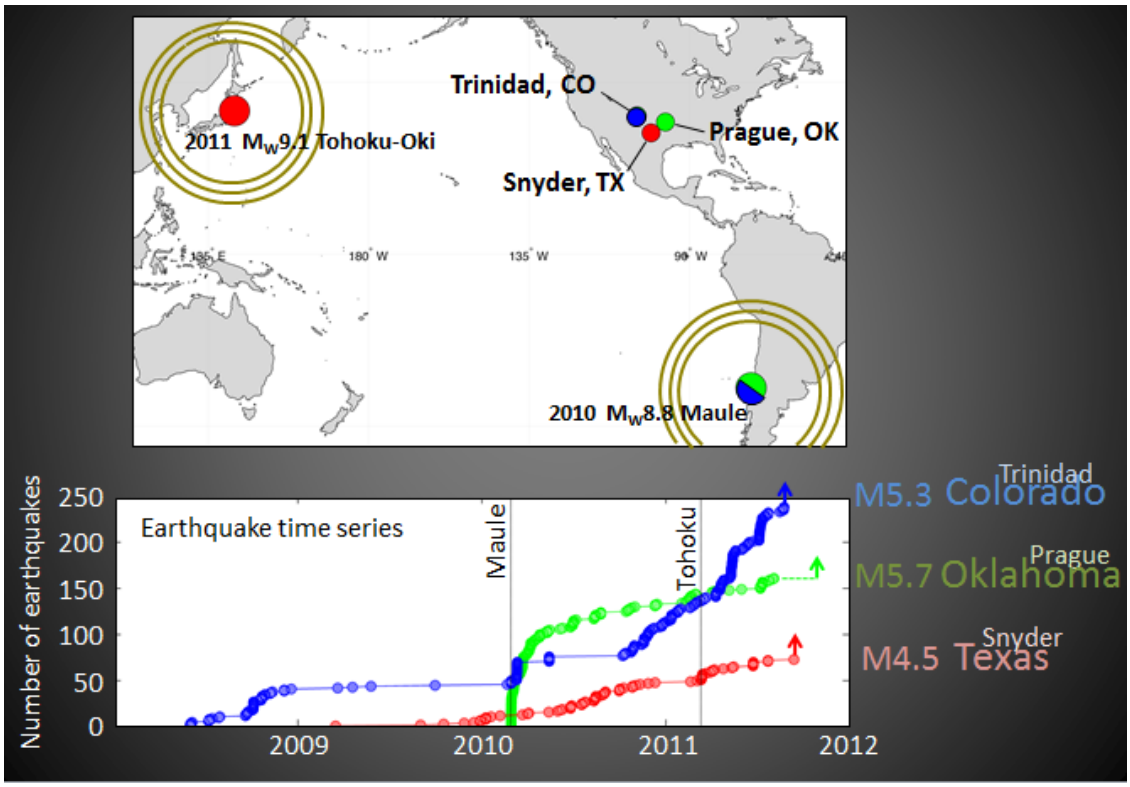
Source: Van der Elst presentation (http://www.iris.edu/spud/gmv/2400)

Figure 7 shows how two major earthquakes (Maule in Chile in 2010, and Tohoku-Oki in Japan in 2011) each triggered many earthquakes at three sites in the United States (Trinidad, Colorado; Snyder, Texas; and Prague, Oklahoma). However, no other locations in the central part of the United States showed remote triggering from the Japanese and Chilean quakes. Van der Elst pointed out three common features of those sites:

- They had experienced long-term injection from one or more disposal wells.
- There were in a state of seismic quiescence.
- Large earthquakes were potentially looming.

Van der Elst suggests that remote triggering reveals critically stressed faults. He further notes that proper monitoring of long-term injection sites may give warning of upcoming swarms of anthropogenic earthquakes.

Figure 7 – Earthquakes Triggered at Three U.S. Sites



Source: [Van der Elst presentation]

Chapter 6 – Evaluating the Risk of Induced Seismicity

6.1 Do Injection Wells Cause Earthquakes?

There is some compelling evidence from a limited number of sites that injection of fluids in high volume over an extended period of time has the potential to cause earthquakes. Many of the earthquakes are very small and are not felt, but at some locations, injection wells have led to one or more felt earthquakes.

Holland offers several examples using well-known earthquake sites. He included one chart in his presentation that plotted the maximum seismic moment as a function of total injected volume for 16 different locations. All of the large magnitude events are associated with wastewater disposal wells. The data points show a relatively strong linear trend. He also presented data from Rangely, Colorado and Rocky Mountain Arsenal that showed a strong temporal trend between number of earthquakes and the injected volume.

Holland noted that the number of larger induced earthquakes may increase with continued injection. This has been observed in various induced seismicity cases. He also cited the example of Rocky Mountain Arsenal where earthquakes continued and grew larger after injection ceased. This phenomenon was the result of elevated pore pressures persisting in the fault zone for several years after injection operations had stopped.

Holland also stated that induced earthquakes are typically found close to the well, but they may migrate away over time. For example, the long-term injection program at Paradox Valley, Colorado resulted in some earthquakes occurring more than 8 km away from the injection well.

Van der Elst offered similar data. He described the swarms of earthquakes at Guy, Arkansas and Youngstown, Ohio. Both sites had high injection pressure and showed close temporal and spatial correlation between the number and size of induced earthquakes and the injected volume. He added that there were at least five large earthquakes located near disposal wells in 2011 alone (M3.9 at Youngstown, Ohio; M4.5 at Snyder, Texas; M4.7 at Guy, Arkansas; M5.3 at Trinidad, Colorado; and M5.7 at Prague, Oklahoma). However, he noted that at other sites in Oklahoma, Colorado, and Texas, the linkage between earthquakes and injected volumes was less clear cut.

6.2 Do All Injection Wells Lead to Earthquakes Felt at the Surface?

There are numerous injection wells in the United States. Nygaard suggests that about 140,000 Class II injection wells are used across the country. Matthew Weingarten of the University of Colorado-Boulder cited a slightly higher number (168,000) of Class II wells based on a 2011 U.S. Environmental Protection Agency (EPA) report. Out of that total, more than half are used to reinject produced water into hydrocarbon producing formations for enhanced recovery operations. Less than half are used as disposal wells, which inject oil and gas fluids into non-producing formations. Further, hydraulic fracturing is conducted on tens of thousands of wells each year. A smaller number of wells are used for injection at geothermal sites.

If felt seismicity were induced equally by all of those activities, there would be thousands of reports of felt earthquakes in many states each week. Yet the relatively small number of felt earthquakes associated with energy production activities suggests that not all individual injection activities pose the same degree of risk.

Nygaard suggested that the NAS report (which was prepared by a committee of experts) made it clear that not all injection creates same level of risk, and there is relatively small number of earthquakes with appreciable ground shaking relative to the total number of injection wells or hydraulic fracturing wells. Holland noted that a recent publication by a USGS seismologist, William Ellsworth, emphasized that most U.S. wastewater disposal wells have no detected seismicity within tens of kilometers and that in California, the majority of the 2,300 active wastewater injection wells are located in regions of low seismicity.

Van der Elst offers a somewhat different interpretation of this situation. He noted in written comments provided to the author following the session: *"while most injection wells are not associated with induced earthquakes, over the last decade over half of the earthquakes greater than magnitude 4.5 in the Midwest have been located at or near fluid injection sites. This means that while induced earthquakes are indeed quite rare, on a whole they pose a greater hazard than natural earthquakes in the Midwestern U.S.".*

This discrepancy between all injection activities and a much smaller subset that does lead to earthquakes felt at the surface begs for some way of predicting which injection wells or locations are most likely to lead to felt earthquakes. The science to make such predictions is not yet highly refined. An alternative is to operate injection activities under a risk management framework. Section 6.4 describes a framework developed by an oil and gas company. Two risk management frameworks were discussed during the January session, and are described in the first white paper.

6.3 Geospatial Matching of Injection Wells and Earthquakes

Weingarten reported on his efforts to compare the locations of injection wells and earthquakes. He is developing a large database that plans to include the physical locations of all Class II injection wells in 26 states in the mid-section of the United States – the east and west coasts were not included in his study. He then plans to overlay the historical earthquake catalog from the USGS National Earthquake Information Center. He described the difficulties he faced in collecting injection well information from the oil and gas and environmental protection agencies in the individual states or from the EPA regional offices. He noted that some states have readily available information on the Class II injection wells, while others do not. He continues to investigate additional sources of data to augment his current data set.

In the next step, Weingarten employs spatial filtering to identify those injection wells that are located within a 5-km radius of any earthquake epicenter – this conforms with the Davis-Frohlich criteria for identifying an induced seismic event (see Section 2.3). However, in the mid-continent United States, Weingarten reported that USGS seismologists have told him that a 10-km uncertainty about the physical location of an epicenter is a reasonable estimate based on the sparse seismometer coverage in the area. To account for the geographical uncertainty, he draws a virtual 10-km "halo" around the epicenter location. He creates a virtual 5-km "halo" around the injection well location. For an earthquake to be worthy of further review the two halos must overlap.

When the halos do overlap, injection wells are considered to be co-located with the earthquake. In his preliminary efforts, Weingarten found an effective match of co-located earthquakes and injection wells in Arkansas, New Mexico, and Colorado. However the co-located relationship was not as effective in Oklahoma and Wyoming. Weingarten showed an additional slide that employed a temporal filter (the method for this was not described) for the Oklahoma data. After the temporal filter was applied, he was able to see an effective match of earthquake and injection well locations.

Weingarten also found some basins that had many injection wells but few or no earthquakes. Examples of this are:

- Louisiana
- Michigan - Michigan Basin
- North Dakota - Williston Basin
- Colorado/New Mexico - San Juan Basin.

6.4 Risk Management

Kris Nygaard described the technical considerations associated with risk management of induced seismicity in waste-water disposal and hydraulic fracturing operations. He outlined a possible risk management framework based on various technical considerations that were developed by an in-house team at ExxonMobil. Risk is the combination of probabilities and consequences. A standard tool used in risk assessment is a risk matrix approach to identify risk level. With risk level identified, possible risk mitigation approaches can be evaluated. One of Nygaard's colleagues presented an earlier version of the risk management framework during the January session. Nygaard's talk updates several points.

The ExxonMobil protocol uses a matrix with probability on one axis and consequences (expressed as MMI value) on the other axis. The probability criteria include:

- Fluid volume
- Formation character
- Tectonic/faulting/soil conditions
- Operating experience
- Public sensitivity and tolerance
- Local construction standards.

The consequences criteria include:

- Safety/health
- Environment
- Detection by the public
- Financial.

More details on how each of these criteria can be evaluated are provided in Nygaard's presentation. Figure 8 shows the matrix.

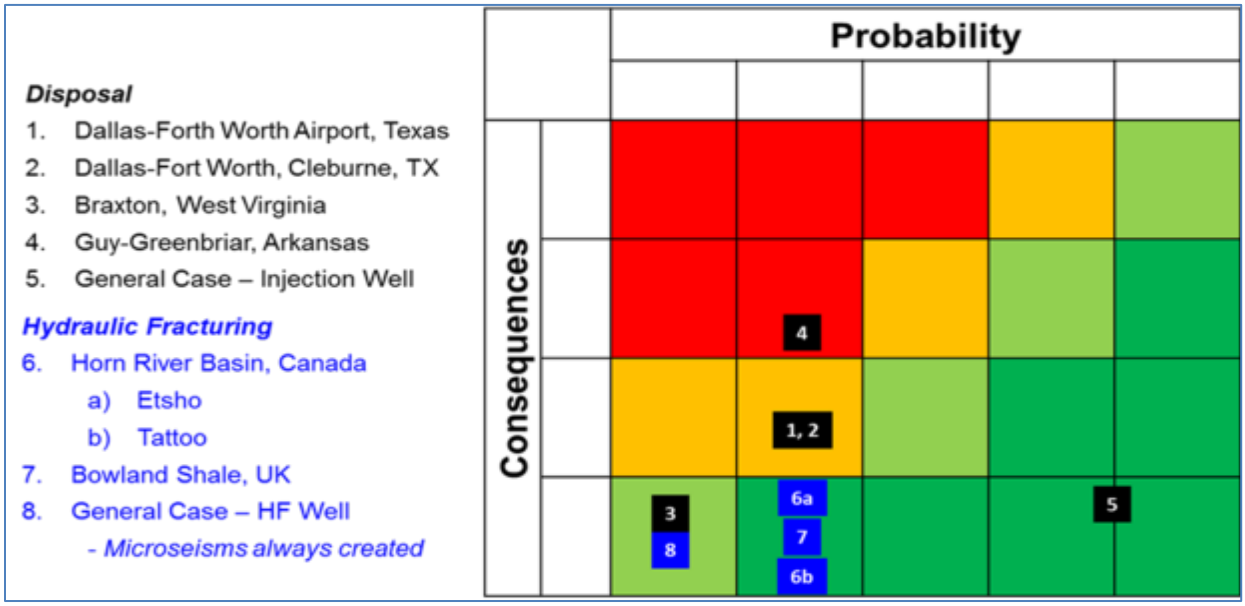
Figure 8 – Risk Matrix Approach for Assessing Potential Induced Seismicity in Wastewater Disposal Wells and Hydraulically Fractured Wells

	Very Likely	Somewhat Likely	Unlikely	Somewhat Unlikely	Very Unlikely
1 MMI > VIII PGA > ~0.34g	High	High	High	Medium	Low
2 MMI : VI - VII PGA > ~0.092g	High	High	Medium	Low	Very Low
3 MMI: V-VI PGA > ~0.039g	Medium	Medium	Low	Very Low	Very Low
4 MMI: II-V PGA < ~0.039g	Low	Very Low	Very Low	Very Low	Very Low

Source: Presentation by Nygaard

To illustrate how the risk assessment methodology could be applied, Nygaard gave examples using four specific injection wells and two specific cases of hydraulic fracturing, as well as the general examples of normal injection well operations and hydraulic fracturing operations (where microseisms are routinely created as part of the stimulation process). Figure 9 shows these examples plotted on the induced seismicity risk matrix. For example, two disposal wells in Texas that were linked to induced seismicity (Dallas/Fort Worth airport and Cleburn)

Figure 9 – Application of Risk Assessment to Example Wells



Source: Presentation by Nygaard

were estimated to have medium risk. The Braxton disposal well in West Virginia was estimated to have low risk. The Arkansas disposal wells were estimated to have high risk. Injection wells in general were estimated to have very low risk. Three specific hydraulic fracturing projects (two Canadian projects and the Blackpool site in the United Kingdom) were estimated to have very low risk. Hydraulic fracturing in general always creates microseisms but that the risk would be low (i.e., high probability, but low consequence).

After the risk level is estimated, possible risk mitigation approaches can be evaluated in terms of their effectiveness and cost. Nygaard noted that ExxonMobil would encourage a stoplight approach for high seismicity risk areas. Projects with estimated high risk would need to consider suspending operations. If they did continue, risk mitigation would be used. Projects with medium risk would adjust operations and consider steps to mitigate risk. Projects with low or very low risk would continue operations as normal.

Nygaard offered some concluding perspectives:

- Approaches to assess and manage seismicity risk should be based on sound science and take into account the local conditions, operational scope, geological setting, historical baseline seismicity levels. They should reflect reasonable and prudent consideration of engineering standards and codes related to seismicity structural health.
- Seismicity monitoring and mitigation should be considered in local areas where induced seismicity is of significant risk, such as in areas where:
    - Significant seismicity (above historical baseline levels) has actually occurred and sound technical assessment indicates that the seismicity is associated with fluid injection operations, or
    - If sound technical assessment indicates the local area may possess significant risk associated with potential induced seismicity.
- In local areas where induced seismicity poses significant risk, appropriate monitoring and mitigation should include:
    - A mechanism to alert the operator in near real-time to the occurrence of seismicity significantly above local historical baseline levels, and
    - A procedure to modify and/or suspend operations if seismicity levels increase above threshold values for maintaining local structural health integrity and minimizing secondary damage.
- Mitigation controls, if implemented, should consider completion practices and operational complexity, as well as considering the risk level.

6.5 Oklahoma's Draft Best Practices for Siting and Operating Injection Facilities

Holland described a group of eight best practices that are currently under development by the Oklahoma Geological Survey. They are expected to be released in draft form during the fall of 2013. They are listed below as an example of the types of measures being considered by a state agency. Holland's presentation gives more detail on most of the practices.

1. Fluid injection near known faults should be avoided.
2. Fluid injection wells should be sited further from faults that are favorably oriented within either the regional or local stress field.
3. Injection pressure and volume should be monitored and recorded frequently during the operation of the well.
4. Formation pressure should be monitored as often as practical. However, at a minimum, regular shut in, pressure fall-off tests should be conducted to measure formation pressure.
5. Injection into crystalline basement rock layers should be avoided.
6. The siting of new injection wells in higher risk environments should be approached with caution.
7. In cases where fluid injection is occurring in higher risk environments, additional geotechnical information may help to provide further constraints on injection limits.
8. The operator should have a plan in place to recognize and respond in a timely manner to unexpected seismicity or changes in injection pressure or volume.

Chapter 7 – Regulatory Considerations

The final portion of the special session included remarks from several states describing the efforts that had been made to respond to induced seismicity events and to establish regulations relating to induced seismicity. The moderator limited each state speaker to just a few minutes, so the resulting discussions were brief, and the summaries are not detailed.

7.1 Arkansas

Lawrence Bengal of the Arkansas Oil and Gas Commission (AOGC) began by stating the earthquakes are local and do not occur around every injection well. He described the earthquake swarm around the previously unknown Guy-Greenbrier fault beginning in 2010. During 2010, seismicity continued along the fault. In January 2011, the AOGC placed a permanent moratorium on permitting any new or additional Class II disposal in a large area surrounding the Guy-Greenbrier and Enola seismically active areas. The three disposal wells that were believed to have triggered the earthquakes were closed and plugged. The AOGC required seismic monitoring conditions to the permits of other disposal wells that are located outside of the moratorium area. Since the moratorium was imposed, the seismic rate has decreased.

7.2 Colorado

Thom Kerr of the Colorado Oil and Gas Conservation Commission (COGCC) stated that the COGCC is aware of causes of the earthquakes at Paradox Valley and continues to acquire additional data on the Raton Basin injection wells and local earthquakes. At this time, Colorado has no state regulations regarding disposal wells and induced seismicity.

The COGCC permits require injection below fracture pressure. They also set a specific limit on the volume that can be injected. This limit is calculated on the formation capacity within a ¼-mile radius of the injection well.

7.3 Texas

Leslie Savage of the Railroad Commission (RRC) of Texas stated that a great deal of uncertainty surrounds the issue of induced seismicity. She noted that seismic activity observed in Cleburne, DFW Airport, and Timpson are examples of induced seismicity. With over 25,000 injection wells in Texas, such occurrences are extremely rare. Her agency is reluctant to develop costly induced seismicity regulations without additional science to pinpoint conditions that increase

the level of risk. The RRC continues to follow the research. The RRC requires injection below fracture pressure.

7.4 Ohio

Tom Tomastik of the Ohio Department of Natural Resources (ODNR) described how the ODNR responded to the December 2011 earthquakes in Youngstown, Ohio by stopping permitting of any new disposal wells. The ODNR started to issue new Class II saltwater injection well permits again in November 2012 after adopting new regulations. He noted that most of the seismicity results from injection into the deep Precambrian basement rock. The new permits require a variety of additional monitoring requirements, including continuous monitoring of the injection and annulus pressures to maintain mechanical integrity. The ODNR does not allow injection above fracture pressure.

Tomastik described ODNR seismic monitoring efforts. The agency hired a seismologist and began installing portable seismic monitoring stations around a few of the new Class II injection well sites. Monitoring will begin before injection starts and will continue to monitor for 6 to 9 months after initiation of injection operations. If no evidence of larger seismic events is found, the portable seismic stations will be moved to another new disposal well location. ODNR currently has 12 portable seismic stations that are monitoring in real time; they hope to obtain an additional 12 stations.

Tomastik suggested that decisions should be based on sound science, and should reflect consideration of multiple lines of evidence.

7.5 Pennsylvania

Joe Lee of the Pennsylvania Department of Environmental Protection noted that there are very few disposal wells in Pennsylvania, primarily due to competition with gas storage facilities at depleted gas plays and availability of surface disposal options. He also noted that Pennsylvania experiences very few earthquakes – most of them occur in portions of the state that are not undergoing oil and gas activity

7.6 Oklahoma

Lori Wrotenbery of the Oklahoma Corporation Commission (OCC) reported that Oklahoma has a large number of disposal wells and a large number of earthquakes, both of which are widely

distributed across the state. Some areas in the state show a possible correlation between injection and earthquakes, while other areas do not. The OCC is supporting the research by providing data and contributing to the expansion of the state's network of seismic monitoring stations. They are following a version of the stoplight approach that considers the risks posed on a site-by-site evaluation.

As noted in Chapter 6, the Oklahoma Geological Survey is developing draft best practices for siting and operating injection facilities.

7.7 EPA Region 6

Phil Dellinger of EPA Region 6 was in the audience. During the question and answer session, he offered the following information. EPA's National Technical UIC Workgroup is conducting a literature survey on induced seismicity focused on four case examples. EPA is preparing a "lessons learned" document and hopes to send it to EPA headquarters soon.

7.8 International Examples

Nygaard's presentation included two examples of how agencies in Canada and the United Kingdom are regulating injection activities as related to induced seismicity using different forms of a stoplight approach. These examples are shown below.

7.8.1 Horn River, British Columbia, Canada

The British Columbia Oil and Gas Commission established a regional seismic monitoring system. Seismic events should be reliably detected and reported at or above magnitude 2.0. The Commission will contact an operator if seismicity is detected; at magnitude 2.0, mitigation discussions begin. There will be a unique response for each case. Operations will be temporarily suspended for earthquakes with magnitudes ≥ 4.0.

7.8.2 Bowland Shale, England, United Kingdom

The UK Department of Energy and Climate Change (DECC) established a rigorous set of requirements before allowing hydraulic fracturing to proceed. Note that these requirements apply just to fracturing – disposal wells are not permitted in the UK. Operators will first be required to review the available information on faults in the area of the proposed well to minimize the risk of activating any fault by the fracturing process. Operators will be required to monitor background seismicity before operations commence. Real time seismic monitoring will

also continue during operations, with these subject to a “traffic-light” approach so that operations can be quickly paused and data reviewed if unusual levels of seismic activity are observed.

Each stage of the frac (normally a horizontal well is fractured in a series of linear sections or stages of several hundred feet in length) will be carefully designed to use just enough fluid to create a fracture sufficient to enable gas to flow. A flowback period will be required immediately after each stage to rebalance the pressures. Nygaard noted that this flowback requirement if/when applied in horizontal wells will significantly increase operational complexity, and cost. Flowback is not normally performed between frac stages in horizontal wells because this leads to inadvertent plugging of wells when the proppant also flows back into the well.

Real-time recording of earthquakes during and for 24 hours after each stage of the frac will be analyzed to look for abnormal induced events amidst the normal background seismicity. Any seismic events greater than or equal to magnitude 0.5 will result in immediate stoppage of injection.

Chapter 8 - Review of Major Issues and Findings

This chapter lists a few of the major issues and findings discussed during the special session.

1. Natural seismic events (earthquakes) occur regularly in many locations, but most of them are very small in magnitude and are not felt by humans at the surface, nor do they cause damage to surface structures. The Richter and Moment Magnitude scales measure the size of the wave on a seismograph, whereas the Modified Mercalli Intensity measures the extent of impact occurring at the surface to people and structures.

2. Many of the seismic events are naturally occurring, but some can be caused by human activities, often from injection of fluids. These are referred to as "induced seismicity". Several of the presenters mentioned the observation that the number of induced seismic events has been increasing in recent years. Several ongoing research projects were described that may better quantify the number of induced earthquakes in the future.

3. The 2008 version of the USGS National Seismic Hazard Maps (the most recent version) does not account for many induced earthquakes. Increased hazard from induced seismicity may be included in the next update to the hazard maps, to be available in 2014. As a result, building codes may be strengthened, and insurance rates could rise.

4. Over 150,000 Class II injection wells inject fluids every day across the United States. Further, hydraulic fracturing is conducted on tens of thousands of wells each year. A smaller number of wells are used for injection at geothermal sites. Most of these cause no earthquakes or create seismic events with such small magnitudes that they cannot be felt at the ground surface. However, injection activities at a small number of locations (white paper II mentions a dozen or so of these as well-documented cases) have created earthquakes that are felt at the surface.

5. Some local earthquakes may be triggered by large earthquakes that occur hundreds or thousands of miles away. The seismic waves released by large earthquakes travel through the earth's crust. When conditions at a local site are primed and favorable (e.g., high fluid pressure conditions), the passing waving may generate new earthquakes. One speaker noted that when observed at fluid injection sites, these long-range triggered earthquakes may suggest a link between local earthquakes and fluid pumping.

6. Some agencies and industry groups recommend the use of a risk framework that employs a stoplight approach. Injection activities are evaluated for their probability of causing earthquakes and the consequences of any earthquakes that do occur. Thresholds for risk

tolerance can be set to allow operations to proceed until seismic events with magnitudes at or above the threshold are observed. At that point additional monitoring and/or cessation of injection can be required. Examples from British Columbia and the United Kingdom follow a stoplight approach for evaluating induced seismicity. But the two locations employ a significantly different risk threshold (magnitude 2.0 for British Columbia, and magnitude 0.5 for the UK).

7. The ability to detect and pinpoint the location of individual earthquakes and swarms of earthquakes depends to a large degree on the spacing of seismic monitoring stations and how close a seismic event occurs to a station. The seismologists who spoke during the session all commented on the shortage of existing data and stations for collecting new data. Several speakers mentioned the Transportable Array (TA) a collection of densely-spaced seismic monitoring stations that are relocated periodically to different U.S. locations. During the periods when the TA was located at certain regions, the closely spaced array of stations contributed a great deal of additional information that could not have been gained from the standard national network of stations.

8. Most state regulatory agencies do not have regulations that focus specifically on induced seismicity. However, Ohio and Arkansas developed regulations following large earthquakes associated with disposal wells. Oklahoma is developing best practices. States are following the research.

Appendix A – Agenda for Special Session

Assessing & Managing Risk of Induced Seismicity by Underground Injection: A Special session for seismologists, regulators, and other stakeholders

September 23, 2013

Moderator: Lori Wrotenbery, Oklahoma Corporation Commission
Part 1 - Researchers presenting findings and research strategies

- Abstract 47: Induced Seismicity from Fluid Injection and Draft Best Practices - **Austin Holland**, Seismologist, Oklahoma Geological Survey, Univ. of Oklahoma
- Abstract 21: Seismic Response to Power Production at the Salton Sea and Coso Geothermal Fields, CA: Using Operational Parameters to Study Anthropogenic Seismicity Rates **- Lia J Lajoie**, Fugro Consultants, Inc.
- Abstract 22: Enhanced Remote Earthquake Triggering at Fluid Injection Sites in the Midwestern U.S. - **Nicholas J. van der Elst**, Columbia University
- Abstract 7: USGS Earthquake Research on Injection-induced Seismic Activity: a Progress Report - **Evelyn Roeloffs**, USGS

Part 2 - Strategies: Initiatives and technology used to limit risk

- Abstract 38: Technical Considerations Associated with Risk Management of Induced Seismicity in Waste-Water Disposal & Hydraulic Fracturing Operations - **Kris J. Nygaard**, ExxonMobil Production Co.
- Abstract 33: Compiling and Interpreting Class II Injection Well and Seismicity Data in the U.S. Mid-Continent to Identify Zones of Induced Seismic Hazard - **Matthew Weingarten**, University of Colorado-Boulder

Part 3 – Regulatory - State Panel

- **Larry Bengal**, Arkansas
- **Thom Kerr**, Colorado
- **Leslie Savage**, Texas
- **Tom Tomastik**, Ohio
- **Joe Lee**, Pennsylvania
- **Lori Wrotenbery**, Oklahoma