Fracking Industrialization & Induced Earthquakes

The Mechanisms that Connect the Disposal of Fracking Wastewater into Deep-Injection Wells to a Significant Increase in Midcontinent Seismic Activity

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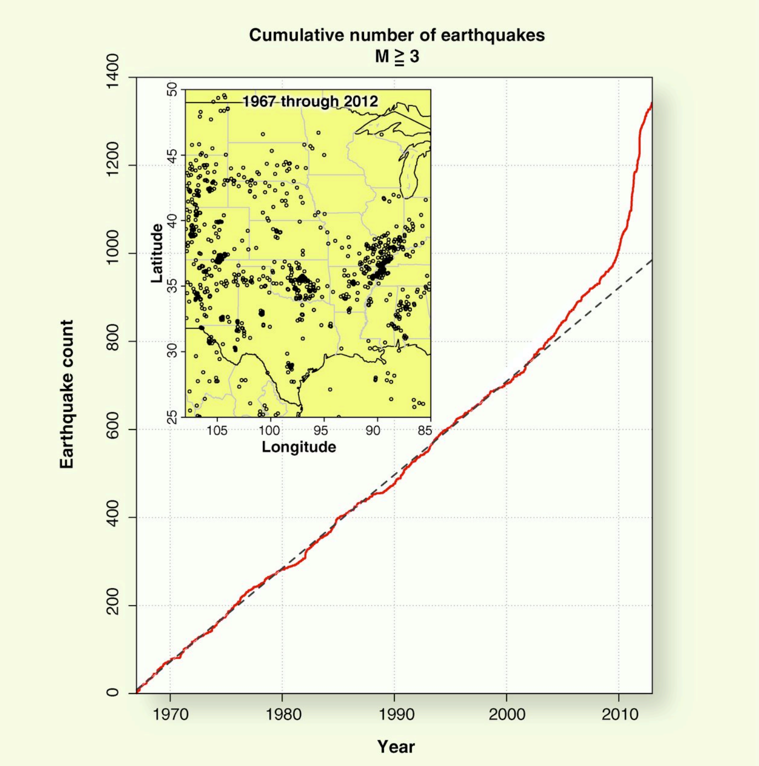


Cumulative count of earthquakes with magnitude ≥ 3.0 in the central and eastern United States, 1967–2012. The dashed line corresponds to the long-term rate of 21.2 earthquakes/year.
(Inset) Distribution of epicenters in the United States midcontinent region.

Introduction

This paper explores the recent significant increase in *felt earthquakes* in the midcontinent of the United States over the past decade in relation to fracking industrialization and its associated voluminous wastewater disposal needs. Studies and expert insight from geologists and seismologists from over the past fifty years will be utilized in order to render evidenced-based conclusions regarding these matters that have often remained at the opinion level of discourse in the public sphere.

The current extent of U.S. fracking industrialization will be reviewed, including dissection of shale oil and gas production levels, the scale of proliferation of fracking wells, the volume of toxic and radioactive effluent, fracking flowback and produced wastewater disposal needs, and the impact of the exponential growth in deep-injection disposal well usage on the United States' current seismic reality. Two important limiting conditions, the *impervious* unknowns regarding subterranean geological formations *and* the fact that disposal wells will fail and leak, provide context for discussion of our obscured yet viable long term understanding of the mechanisms underlying the whole phenomenon of fracking wastewater disposal induced earthquakes.

Historic Shift in Frequency of Midcontinent Earthquakes

Seismologists like the U.S. Geological Survey's William Ellsworth started noticing a historically unique trend about a dozen years ago, "that there were an unusual number of earthquakes in the middle of the country," in areas that have not been known for earthquakes (Rugh, 2013). The Guy-Greenbrier area of Arkansas, with total population of just over 5,000, was traditionally a quake-free area. Throughout all of 2007 the area had only one earthquake of magnitude 2.5 or greater, followed by only two such quakes in 2008. However, in 2009 there were 10, and in 2010 there were 54 earthquakes of magnitude 2.5 or greater (Kerr, 2012). On February 27, 2011, Guy experienced a magnitude 4.7 earthquake.

Neighboring state Oklahoma went through a similar pattern as a whole, experiencing just a few earthquakes per year from 1972 to 2007, 12 in 2008, 50 in 2009, and more than 1,000 in 2010, culminating with a magnitude 5.7 earthquake on November 6, 2011. While Oklahoma saw a more than hundred-fold increase in overall earthquakes, it also saw a twenty-fold increase in earthquakes with magnitude 3.0 or greater in those same three years from 2008 to 2010 (Ellsworth et al, 2012). Meanwhile, the Barnett Shale region of north central Texas has experienced "unprecedented levels of seismicity" since shale gas development began in late 1998, with "nine earthquakes of magnitude 3.0 or larger occurred, compared with none in the preceding 25 years." Overall, the states reporting unusually elevated levels of seismic activity include Arkansas, Colorado, New Mexico, Ohio, Oklahoma Texas, and Virginia (Ellsworth, 2013).

This pattern seen in both localized and statewide contexts is also reflected in data concerning the frequency of magnitude 3.0 or greater earthquakes in the entire U.S. midcontinent region, with the annual number of magnitude 3.0 or greater earthquakes having "increased almost tenfold in the past decade" (Lovett, 2013). The "middle part of the continent" went from a remarkably consistent average 21 per year from 1970 to 2000, to an average of 29 per year from 2001 to 2008, to 50 magnitude 3.0 or greater quakes in 2009, to 87 in 2010, to somewhere in the range of 134 to 188 in 2011 (Demus, 2012; Ellsworth, 2013; Henry, 2012; Lovett, 2013). As William Ellsworth *et al* (2012) reported in their *Seismological Research Letters* study, "A naturally-occurring rate change of this magnitude is unprecedented outside of volcanic settings or in the absence of a main shock, of which there were neither in this region" (Ellsworth et al, 2012). Especially in areas that have historically lacked earthquakes, like the Youngstown, Ohio area, as Columbia University's Lamont-Doherty Earth Observatory seismologist John Armbruster relates, "Having that many earthquakes […] where there aren't a lot of earthquakes, was suspicious" (Fountain, 2012).

What all these different scenarios share is a common time frame for the onset of fracking industrialization, and an ever-expanding need for deep-injection disposal wells [DIDWs] to handle the massive volumes of associated fracking flowback and produced wastewater. A 2013 *Science* study (van der Elst et al, 2013) by a team of seismologists led by Nicholas van der Elst of Columbia University's Lamont-Doherty Earth Observatory found, "that at least half of the magnitude-4.5 or larger earthquakes that have struck the interior United States in the past decade have occurred near injection-well sites" (Lovett, 2013). A 2013 *Geology* study (Keranen et al., 2013) by a team of seismologists led by Katie Keranen concluded while earthquakes with magnitude 5.0 or greater are a rarity east of the Rocky Mountains, “the number per year recorded in the midcontinent increased 11-fold between 2008 and 2011, compared to 1976–2007” (Keranen, 2013). When interviewed concerning colleague response to the study, Keranen indicated that, “Pretty much everybody who looks at our data accepts that these events were likely caused by injection” (Behar, 2013).

Fracking Wastewater Deep-Injection Disposal Wells and Induced Earthquakes: The Jury’s Verdict

While speculation and confusion dominate the lay population’s conversation regarding the origins of this historic increase in midcontinent earthquakes, there is a strong consensus among geologists and seismologists that the recent uptick in earthquakes is primarily due to the recent increase in fracking industrialization and disposal of its associated wastewater.

William Ellsworth of the U.S. Geological Survey Earthquake Science Center concludes: “Clearly it is happening. Earthquakes have been happening in some unusual parts of the United States. At this point, we do not know if all or just some part of that increase is attributable to industrial activities like wastewater injection” (Vergano, 2013). These risks associated with deep-injection wells inducing earthquakes, which according to Scott Ausbrooks (geologist with the Arkansas Geological Survey) have “been known for decades,” are especially heightened in known seismic zones, such as the Wabash and New Madrid Seismic Zones, as “what is clear… is that deep reservoirs in tectonically active zones carry a real risk of inducing damaging earthquakes” (Ellsworth, 2013).

For Cliff Frohlich, senior research scientist at the University of Texas at Austin’s Institute for Geophysics, the problem is that faults are ubiquitous, they are most everywhere, and “most of them are stuck, because rock on rock is pretty sticky. But if you pump a fluid in there to reduce the friction, they can slip” (Behar, 2013). Frohlich continues regarding the recent uptick in seismic activity, "These earthquakes could have been anywhere. They weren't. Virtually all of them were near injection wells" (Behar, 2013).

Popular Science writer Francie Diep notes a strong consensus among those best equipped to comprehend the situation: “Since companies began doing [wastewater deep-injection] more often, U.S. Geological Survey and other scientists have noticed more earthquakes occurring in the Midwest, which isn't normally so seismically active. Three different geologists told me this, unprompted, when I was researching the Prague quakes earlier this year” (Diep, 2013). Those Prague, Oklahoma earthquakes included the strongest quake in Oklahoma history, a magnitude 5.7 that struck within a mile of three injection wells filled with fluid leftover from conventional oil dewatering operations (Behar, 2013; Holland & Keller, 2012). The quake destroyed 14 homes, injured two individuals, and was felt more than 600 miles away in Chicago (Choi, 2012; Ellsworth, 2013).

While a team of seismologists from Columbia University, University of Oklahoma and the U.S. Geological Survey concurred on the waste-injection origin of the series of quakes (Keranen et al., 2013), United Kingdom-based applied geophysicist James Verdon points out that, “the Oklahoma Geological Survey has subsequently released a rebuttal (Keller & Holland, 2013) stating that as far as it is concerned, there is not enough evidence to tie the quake to injection activities” (Verdon, 2013a).

Fracking Wastewater DIDWs Are Primary Fracking-Related Seismic Hazard

A team of geologists and seismologists led by William Ellsworth posit in their 2012 study “Are seismicity rate changes in the midcontinent natural or manmade” that the slight increase in seismicity that began in 2001 was primarily due to a Raton Basin coal bed methane field west of Trinidad, Colorado along the Colorado-New Mexico border. They further conclude that the “acceleration in activity that began in 2009 appears to involve a combination of source regions of oil and gas production, including the Guy, Arkansas region, and in central and southern Oklahoma” (Ellsworth et al., 2012).

While some have raised concerned over seismicity related to the fracking event itself, the primary seismic hazard from fracking industrialization is its associated wastewater disposal into Class II deep-injection wells. Shale gas and oil extraction features four behaviors during the entire fracking industrialization life cycle that can induce some degree of seismicity or affect local geological stresses. These include the drilling of wells, the hydraulic fracturing of the shale, the removal of gas and fluids from the well during production, and deep-injection well wastewater disposal (Frohlich et al., 2010).

William Ellsworth points out that with nearly 100,000 wells having been fracked over the last twelve years, the largest induced earthquake from the hydraulic fracturing of the shale was magnitude 3.6, a barely felt earthquake that by itself poses no serious risk.

However, attitudes have shifted regarding wastewater injection induced seismology, as prior to 2011 the seismic event widely accepted by the scientific community as having been the largest wastewater injection induced earthquake in U.S. history was the magnitude 4.8 quake that took place on August 9, 1967 near Denver, Colorado (Ellsworth, 2013). Over the last decade, and especially since 2011, matters have literally shifted.

Shutting Down of Wells that Induced Earthquakes

Geologists and seismologists are not the only engaged professionals raising concerns about fracking wastewater disposal related induced seismology. State oil and gas officials in both Arkansas and Ohio have shut down fracking wastewater disposal wells that have been connected with induced earthquakes. In the case of induced seismology in the Guy-Greenbrier area or Arkansas, the state’s governor, Oil and Gas commission, and the general public all concurred to shut down the responsible injection-wells as, “nearly 1000 recorded quakes had struck the area since the wells had started up” (Kerr, 2012).

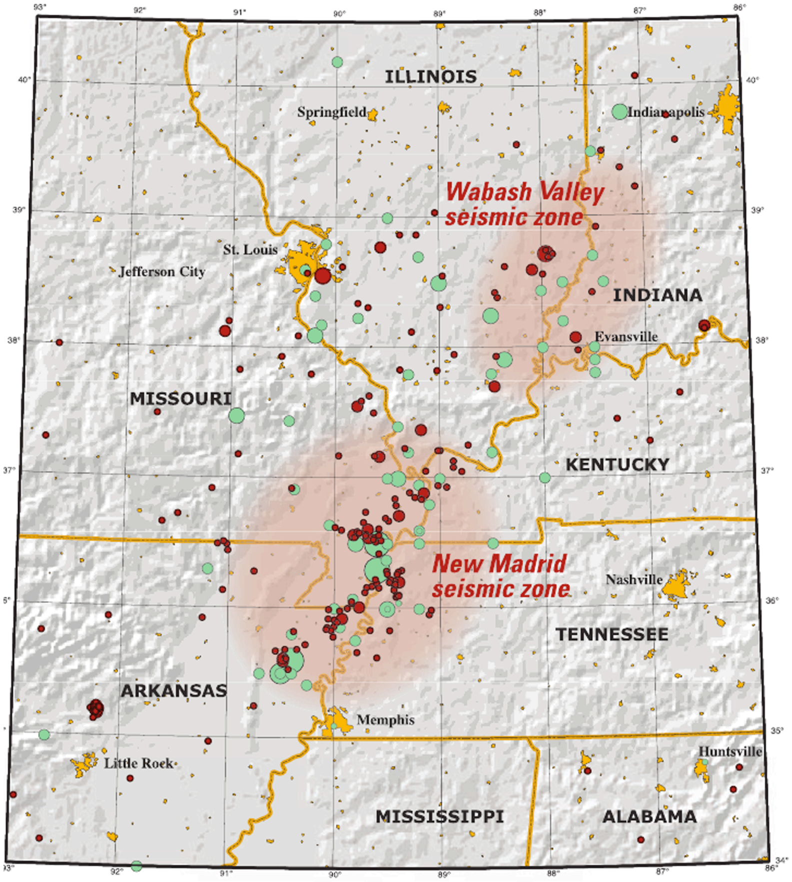
A moratorium was declared within a 1,150 square mile area around Guy-Greenbrier on deep-injection wastewater disposal activities, while seismic-risk studies of the entire Fayetteville shale play were also required. Additionally, “Affected residents filed a class-action lawsuit against Chesapeake Energy and BHP Billiton Petroleum—the first time anyone has sued oil and gas companies for causing an earthquake” (Behar, 2013). University of Memphis seismologist Stephen Horton related that once the wells were shut down the quakes tapered away and ultimately ceased (Kerr, 2012).

The Youngstown, Ohio Fracking Wastewater Disposal Induced Earthquakes

When a magnitude 2.7 earthquake struck near Youngstown, Ohio on December 24, 2011, it was the tenth such earthquake in the 2.0 to 2.7 magnitude range since March of that year connected with fracking wastewater injection well Northstar 1 owned by D&L Energy Group. The well, which came online in December 2010 (just three months prior to start of seismic activity), received the vast majority of its wastewater from fracking projects in Pennsylvania (Fountain, 2012). Nearly 60% of all the fracking wastewater disposed of in Ohio injection-wells in 2012, 257 million gallons, originated in others states, marking a 19% one-year increase in out-of-state fracking wastewater injected into subterranean Ohio (Johanek, 2013). Prior to January 2011 Youngstown, Ohio had not experienced an earthquake dating back to 1776 when scientists first began recording their observations (Choi, 2013).

Upon analysis of the December 24, 2011 earthquake by the Ohio Department of Natural Resources it was determined that the quake originated less than 2,000 feet below the Northstar 1 well (Fountain, 2012). No sooner had the State of Ohio put an immediate cessation to injection at the well, when an earthquake with a 16 times greater magnitude of 3.9 struck the following week, on New Year’s Eve, December 31, 2011. At that point state officials instituted a moratorium on the injection of fracking wastewater within a 5-mile radius of the D&L well until scientists had an opportunity to analyze the data from the string of quakes (Fountain, 2012).

By the time March 2012 rolled around, Youngstown, Ohio had recorded 109 earthquakes in the previous year (Choi, 2013), and “the indications were strong enough to prompt the state to order the



Red circles — indicate earthquakes that occurred from 1974 to 2002 with magnitudes larger than 2.5 located using modern instruments. *(University of Memphis)*

Green circles — indicate earthquakes that occurred prior to 1974. Larger earthquakes represented by larger circles. *(USGS Professional Paper 1527)*

shutdown of four injection wells in the area and issue strong new regulations" (Kerr, 2012). On July 12, 2012 Executive Order (2012-09K) was signed by Ohio Governor John Kasich, which required that operators conduct seismic studies prior to issuance of well permits (Kasich, 2012). Ohio now stands alone in requiring a seismic-risk assessment for all of its injection wells, as every other state, and the federal government, have yet to do (Behar, 2013).

Seismologist John Armbruster puts points out that within a year of the Northstar 1 well opening there were 109 total earthquakes, and "twelve felt earthquakes. After the well was shut down, the number decreased dramatically. You'd need Powerball odds for that to be a coincidence" (Behar, 2013).

Proliferation of Shale Gas & Oil Extraction and Fracking Wells

Over the last decade the United States has seen an unprecedented increase in the proliferation of shale gas and oil extraction that has pushed domestic oil to its current place of highest level of production in 20 years, while bringing natural gas production to an all-time high (Weber, 2013). Shale gas from fracking specifically has gone from only 2% of U.S. natural gas production in 2000 to 23% of NG production in 2010 (US EIA, 2012). Because of fracking, the International Energy Agency projects that the U.S. will overtake Russia as the world's top producer of natural gas by 2015.

With this precipitous increase in shale oil and gas production, the U.S. has likewise seen an increase in the proliferation of fracking wells, with more than 82,000 drilled or permitted in 17 states between 2005 and 2012. At the time of this writing (November of 2013) there are likely in excess of 100,000 fracking wells permitted or drilled in the U.S. (Ellsworth, 2013). In 2012 alone there were 22,326 fracking wells drilled throughout the United States, with more than 60% of them (13,540) being drilled in Texas (Ridlington & Rumpler, 2013). During that year drilling inspectors identified more than 55,000 violations of Texas fracking laws by oil and gas companies (Soraghan, 2013a).

Wastewater Associated with Fracking Industrialization

This dramatic increase in oil and gas production and associated fracking wells has in turn led to an increase in the need for fracking-related wastewater disposal. Each fracked well requires approximately 4 to 7 million gallons of water, fracking fluid and fracking sand to complete a hydraulic fracturing event. In the range of 20% to 80% of the fluid injected during the fracking event, an average of 2.75 million gallons of toxic and radioactive effluent per well ((Hammer & Van Briesen, 2012), returns to the surface as fracking flowback and wastewater (Miller, 2012; Moss, 2008).

The volume of wastewater to be disposed of during the fracking process is one factor that makes fracking industrialization different from anything other form of fossil fuel extraction that has been seen before, producing "50 to 100 times more" waste than conventional oil and gas wells (Cantarow, 2013). Multiply that level of industrialization in terms of number of wells, by that degree of waste management in terms of the volumes of toxic and radioactive effluent per fracked well, and the result is 280 billions gallons of total flowback and produced wastewater coming out of U.S. fracking wells each year (Ridlington & Rumpler, 2013). Unfortunately, these national numbers are woefully incomplete as wastewater produced by Texas alone represents nearly 93% of this total (260 billion gallons), and there was "no estimate" listed for seven of the seventeen fracking states included in the survey.

The shift over the last decade is undeniable, as an overwhelmed Marcellus Shale wastewater disposal infrastructure capacity can attest to, in that "developing the Marcellus shale has increased the total wastewater generated in the region by ~570%" between 2004 and 2012. This of course is a natural consequence of fracking industrialization, as toxic and radioactive wastewater "is an obligate byproduct of current methods and volumes will unavoidably increase with industry expansion" (Lutz et al, 2013).

Various Methods for Disposing of Fracking Wastewater

While there are current alternatives to deep-well injection for disposing of fracking wastewater, scientists and regulators alike agree that the other options are generally far more expensive while embodying additional environmental risks (Lustgarten, 2013a). These alternatives, the first three of which have been utilized extensively in the Marcellus region due to lack of suitable geology for underground injection (MSAC, 2011), include: (1) Processing of wastewater at municipal wastewater treatment facility with final discharge into a local waterway; (2) Processing of wastewater at a private industrial wastewater facility, with either discharge into a local waterway or reuse of the treated effluent in fracking wells; (3) Recycling of wastewater and reuse of the partially treated effluent in fracking wells; (4) Burning of waste; (5) Disposal of waste by application on roadways and other surfaces (Lutz et al, 2013; Lustgarten, 2012a); and unfortunately, (6) "Fracking flowback is dumped into rivers, lakes and reservoirs" (Eco Watch, 2013).

Cliff Frohlich, senior research scientist at University of Texas at Austin's Institute for Geophysics, reminds us that "the people involved in this are going to do the cheapest way of doing things that is generally considered safe" (Henry, 2012a), and that is currently why more than 95% of fracking wastewater is injected into deep wells (Clark and Veil, 2009). Journalist Abrahm Lustgarten, however, reminds us that, "several key experts acknowledged that the idea that injection is safe rests on science that has not kept pace with reality, and on oversight that doesn't always work (Lustgarten, 2012a). It is not just the energy sector that is dependent on this form of waste elimination, as subterranean waste disposal is a cornerstone of the U.S. economy, with pharmaceutical, chemical and agricultural industries all being dependent upon deep-well injection for managing voluminous waste streams. Even carbon storage and sequestration that is the essential fossil fuel industry strategy for addressing climate change, as Lustgarten points out, "counts on pushing waste into rock formations below the earth's surface" (Lustgarten, 2012a).

Fracking Wastewater in Deep-Injection Disposal Wells

As there has been a monumental increase in total fracking-related wastewater produced over the last decade, there has likewise been a dramatic increase in total fracking wastewater injected into disposal wells, where 95% of the toxic effluent is managed. Of the more than 680,000 total injection wells in the United States, in excess of 150,000 fall into the energy industry-specific Class II category that includes both deep-disposal wells in addition to "wells in which fluids are injected to force out trapped oil and gas" (Lustgarten, 2012a). Approximately 30,000 to 40,000 of these Class II wells are deep-disposal wells that receive the volumes of fracking flowback and produced wastewater (Diep, 2013; Ellsworth, 2013; Soraghan, 2013). The states with the most Class II injection wells are Texas (52,016), California (29,505), Kansas (16,658), Oklahoma (10,629), and Illinois (7,843) (US EPA, 2010).

A study by the Argonne National Laboratory estimated that a total of 252 billion gallons of fracking wastewater is injected into Class II deep disposal wells in the United States per year (Clark and Veil, 2009; Clarke et al., 2012). In Texas the total amount of fracking wastewater being injected into deep disposal wells went from 46 million barrels (1.45 billion gallons) in 2005 to nearly 3.5 billion barrels (110.25 billion gallons) in 2011, representing a 76-fold increase in total fracking wastewater injection volume in a six-year period (Galbraith and Henry, 2013). The total amount injected into the more than 150,000 total Class II wells among 33 states is at least 10 trillion gallons of wastewater (Lustgarten, 2012c), while over the last several decades all U.S. industries combined have injected in excess of 30 trillion gallons of toxic liquid into all classes of injection wells, "using broad expanses of the nation's geology as an invisible dumping ground" (Lustgarten, 2012a).

Wastewater Injection Induced Earthquakes – Factors That Increase Risk

As fracking wastewater injection has dramatically increased over the last decade, so have induced earthquakes, as elucidated by Cliff Frohlich: "The earthquakes are occurring more frequently now because there's so much more fluid injection due to the fracking and the development of unconventional gas. […] So what's happened is that we have a lot more injection going on in a lot more places, where we're producing more gas and earthquakes" (Henry, 2012a). While most of the United States' 40,000 wastewater injection wells will never cause felt seismic activity, some have and will induce earthquakes in excess of 3.0, and so far, as great as 5.7 (Diep, 2013; Ellsworth, 2013).

The USGS's Williams Ellsworth identifies a number of factors that could enhance the probability of a given injection-well inducing earthquakes in his 2013 *Science* study. They include, "the magnitude of the perturbation, its spatial extent, ambient stress condition close to the failure condition, and the presence of faults well oriented for failure in the tectonic stress field. Hydraulic connection between the injection zone and faults in the basement may also favor inducing earthquakes, as the tectonic shear stress increases with depth in the brittle crust" (Ellsworth, 2013).

Frohlich likewise stresses that it is absolutely essential to "understand why some injection wells trigger seismic activity and others do not," especially when they seemingly have similar mechanical and geological characteristics. He hypothesizes that "injection only triggers earthquakes if injected fluids reach and relieve friction on a suitably oriented, nearby fault that is experiencing regional tectonic stress" (Frohlich, 2012), such that "the materials must be pre-stressed to a substantial fraction of their breaking strength in order for seismicity to be induced" (Kisslinger, 1976). The specific mechanisms involved in fluid-relieved friction on a locked fault will be explored in greater detail below.

Limiting Condition 1: We Don't Exactly Know What Is Going On Down There

In light of these risk factors identified by Ellsworth and Frohlich, there are two major *limiting conditions* that can significantly contribute to fault rupture and earthquake inducement from fracking wastewater's injection into deep disposal wells. The first is that we do not necessarily know where the injected wastewater is going, and what subterranean pathways it might be following, especially in relation to pre-existing faults both known and unknown. The second is that wells can, and do, fail and leak.

Class II injection wells in practice do not have detailed geologic reviews performed, so there is not particularly any understanding regarding what the well opens up to as much as two and a half miles beneath the surface, including the location of possible faults (Clarke et al., 2012). ProPublica investigative reporter Abrahm Lustgarten captures this reality of disposal well structure: "Tubes of concrete and steel extend anywhere from a few hundred feet to two miles into the earth. At the bottom, the well opens into a natural rock formation. There is no container. Waste simply seeps out, filling tiny spaces left between the grains in the rock like the gaps between stacked marbles" (Lustgarten, 2012a).

The high wellhead pressures applied to inject millions of gallons of fracking wastewater into these deep recesses are sometimes in excess of 50 MPa (493 atmospheres or 7,250 psi) (Hsieh, 1979; Zhang et al, 2013). Injection pressures that high "may cause underground rock layers to crack, accelerating the migration of wastewater into drinking water aquifers" (Lustgarten, 2012b). As Scott Ausbrooks, a geologist with the Arkansas Geological Survey, points out, water will eventually find a way out: "Water does not like to be squeezed. Just like a room of people. The more you put in, the more crowded it gets, and at some point, people are going to start being pushed out the doors" (Behar, 2013). Cliff Frohlich describes the wastewater as being forced "downward and outward" from excessive injection, adding that fracking's toxic effluent "can meander for months, creeping into unknown faults and prying the rock apart just enough to release pent-up energy" (Behar, 2013).

Limiting Condition 2: Deep-Injection Disposal Wells Will Fail and Leak

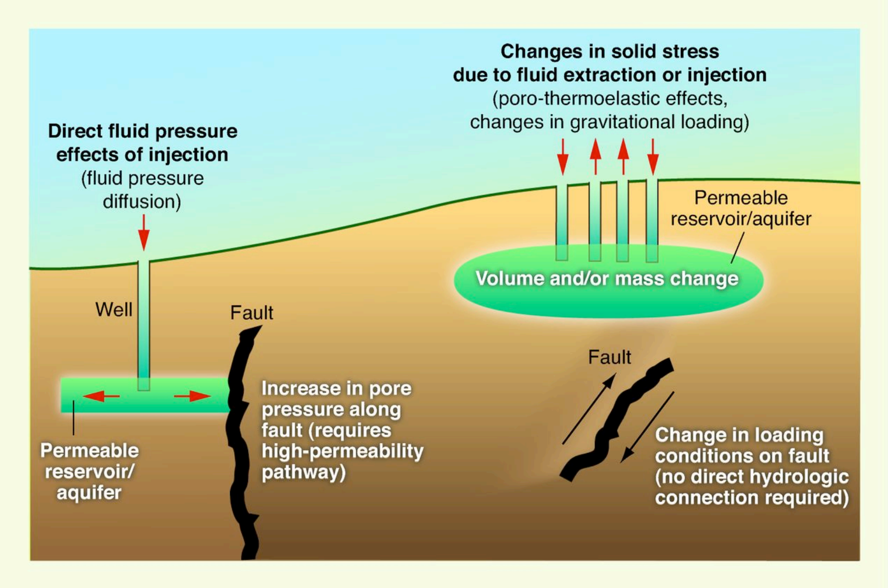
While scientists and federal regulators generally acknowledge they do not know how many of the Class II injection well sites receiving fracking wastewater are leaking, a ProPublica analysis of EPA data and case histories from October 2007 to October 2010 regarding more than 220,000 well inspections shows that 3.2% of the wells failed and "showed signs that their walls were leaking" (Lustgarten, 2012a). ProPublica*'s* Abrahm Lustgarten further related, "records also show wells are frequently operated in violation of safety regulations and under conditions that greatly increase the risk of fluid leakage and the threat of water contamination."

According to federal water protection regulation descriptions more than 7,500 well test failures from those three years studied involved *fluid migration* and *significant leaks*, with most of those failures being due to cracks or holes that have damaged the well structure itself (Lustgarten, 2012a). Williams Ellsworth notes that while the current wastewater deep-injection disposal well regulatory framework was designed to protect aquifers and groundwater sources from contamination, the regulations fail to address seismic safety (Ellsworth, 2013).

Because of the *limiting conditions* that we do not necessarily know where the injected wastewater is going and that deep-injection wells fail and leak at an estimated rate of 3.2%, wastewater migrates not only to areas unknown, but also to regions where we specifically do not want it to go: fault zones. These fault zones tend to be located deep beneath the surface in the region of the lithosphere known as the Precambrian Crystalline Basement.

Fracking Wastewater Injection and Induced Seismology

William Ellsworth noted in his 2013 *Science* study that, "There has been a growing realization that the principal seismic hazard from injection-induced earthquakes comes from those associated with disposal of wastewater into deep strata or basement formations" (Ellsworth, 2013). The operative notion is that in order for seismic activity to be induced, not only does that fault have to be pre-stressed, but it also must be reachable where they are located in the Precambrian crystalline basement by the meandering injected wastewater and its associated fluid pressure. Cliff Frohlich



reiterates this point during a 2012 interview, suggesting "fluid injection may trigger earthquakes only if fluids reach and relieve friction on a nearby fault" (Choi, 2012).

A consensus among geologists support the understanding that a vast majority of the fracking wastewater DIDW induced earthquakes did not originate within the sedimentary reservoirs into which the toxic and radioactive fluid was directly injected. Rather this seismicity originated within the generally impermeable metamorphic and igneous crystalline basement that lies 1 to 6 kilometers deeper beneath the sedimentary platform (Horton, 2012; Hsieh and Bredehoeft, 1981; Nicholson and Wesson, 1990; Seeber et al., 2004; Zhang et al., 2013).

Zhang et al., in their 2013 *Groundwater* study, stated that the ever-increasing midcontinent earthquakes "probably occurred along faults that were likely critically stressed within the crystalline basement." More specifically, they found that induced seismic activity was a result of the fracking wastewater either, 1) being injected into a basal sedimentary reservoir that lacks a confining unit underneath the injection reservoir horizon, thus allowing for migration into Precambrian layers, or 2) being injected "directly into the underlying crystalline basement complex" (Zhang et al, 2013).

Migrating Fluid and Precambrian Crystalline Basements

An essential practical conclusion from the *Groundwater* study (Zhang et al, 2013) is the factor that has the single largest impact in preventing seismic induction within the underlying crystalline basement is the presence of a confining unit barrier between the sedimentary reservoir and the lower Precambrian layer. William Ellsworth describes those injection wells that "dispose of very large volumes of water and/or communicate pressure perturbations directly into basement faults" (Ellsworth, 2013) as problematic disposal wells. Geophysicist Barry Raleigh, whose 1976 *Science* study "An experiment in earthquake control at Rangely, Colorado" demonstrated how earthquakes could be turned on and off by utilizing manipulation of fluid pressure, elucidates that the deep, low-permeability, brittle igneous and metamorphic rock of the crystalline basement "doesn't have a lot of capacity for taking any of these fluids. As a storage medium, they're pretty crappy" (Kerr, 2012).

Readily *felt earthquakes* larger than magnitude 4.0 that have been induced by injection of fracking wastewater into deep disposal wells additionally point to a deeper subterranean origin to these larger earthquakes. "Burdened by far more overlying rock, the deep rock is already carrying stress that," when combined with "the added pressure of the injection trigger," manifests conditions ripe for fault rupture and potentially destructive seismic activity (Kerr, 2012). Zhang et al. (2013) hypothesize that "elevated pore pressures could propagate downward along distributed fracture networks or along conductive fault zones in Precambrian crystalline rocks" (Zhang et al, 2013), meaning that the pressure from fluids can be potentially transmitted to hidden fractures at great depths, given the right conditions. In fact, David M. Evans, in his seminal 1966 *Geotimes* study, relates that even "if the Precambrian fracture system extends to a depth of 12 miles, then fluid pressure could [still] be transmitted to that depth by moderate surface injection pressure as long as the fracture system is open for transmission of that pressure" (Evans, 1966).

The Long Understood Relationship Between Subterranean Fluid Disposal & Induced Seismology

Some may point to 77 CE Rome for the origins of the human demonstration of the relationship between elevated fluid pressure and induced geological failure, a well-documented case in which Romans utilized the technique to "undermine and instantly remove vast quantities of mountainside to extract gold from the buried mother lode at Las Médulas in northwest Spain" (Goodway, 2012). Others might claim that we have shared this understanding for almost a century, such as members of the Committee on Induced Seismicity Potential in Energy Technologies, who claim that "induced seismic activity has been documented since at least the 1920s" (Clarke et al., 2012), referencing a 1926 study that ran in the *Bulletin of the Seismological Society of America* regarding "Local subsidence of the Goose Creek oil field (Texas)" (Pratt and Johnson, 1926).

While these obscure examples add clarity to this generally familiar yet elusive phenomenon, it is David M. Evans' 1966 *Geotimes* study "Man-made earthquakes in Denver" that is popularly credited with establishing the connection between injection of waste fluids and induced earthquakes (Choi, 2012; Ellsworth, 2013; Frohlich, 2012; Henry, 2012; Kerr, 2012; Soraghan, 2013), such that "since 1966, scientists have generally agreed that injection may induce earthquakes in tectonically favorable situations" (Davis and Frohlich, 1993). Keep in mind that Plate Tectonic Theory did not come into general acceptance until just one-year prior, in 1965, to the verification of this form of human induced earthquake phenomena.

The Mechanisms Underlying Earthquakes Induced by Fracking Wastewater DIDWs

In regards to the fracking wastewater disposal-induced earthquakes that have been escalating in frequency in the United States' midcontinent over the last decade, U.S. Geological Survey's William Ellsworth concludes that the mechanism responsible for inducing this seismic activity is the "well-understood process of weakening a preexisting fault by elevating the fluid pressure" (Ellsworth, 2013). Ellsworth clarifies that the three specific events that can trigger the nucleation of an earthquake by bringing the fault to failure are, 1) reducing the effective normal stress on a locked fault, 2) increasing the shear stress along a fracture plane, and 3) elevating the pore pressure of the fluid in the rock. Nucleation is the process that marks the beginning of an earthquake with an initial rupture that propagates along the fault surface. Fault failure or slippage can trigger this process, and in turn, generate an earthquake (Ellsworth, 2013).

Effective Normal Stress and Induced Seismology

If the effective normal stress, the frictional forces that hold a fault a place, is lowered, it can result in fault slippage and trigger earthquake nucleation. Increased fluid pressure relieves enough of squeeze on the fault to release it and induce an earthquake (Kerr, 2012). Injecting fluids that act as a pressurized cushion to relieve the effective normal stress that keeps a fault locked over-pressures a fault (Sheppard et al, 2013). Heather Savage, a geophysicist at Columbia University's Lamont-Doherty Earth Observatory, relates that, "When you over-pressure the fault, you reduce the stress that's pinning the fault into place and that's when earthquakes happen" (Earth Institute, 2013).

Effective normal stress is equal to the difference between the applied normal stress and pore pressure (Ellsworth, 2013). Applied normal stress is the total stress on a rock (Hsieh, 1979), or the weight of a given block (Evans, 1966), and pore pressure is the pressure of fluid in the rock's pores and fractures (Ellsworth, 2013), such that increased pore pressure causes a decrease in frictional force, the effective normal stress (Warpinski, 2012).

Shear Stress and Induced Seismology

Raising or increasing the shear stress along a fracture plane can also result in induced seismology, such that once the shear stress overcomes the effective normal stress (multiplied by the coefficient of friction and added to cohesion) in a geological system, the fault will slip, fail, and result in an earthquake (Warpinski, 2012). Faults are locked due to frictional forces, which are the result of in situ stresses pressing vertically on the fault plane. Raising the shearing stress to the point of overcoming effective normal stress such that the fault slips is also known as the Mohr-Coulomb failure criterion. Paul Hsieh, recently named 2011 United States Federal Employee of the Year for his role in bringing to a close the BP oil spill in the Gulf of Mexico, remarks in his pivotal 1979 master's thesis that, **"**Shearing stresses will remain the same no matter how pore pressure varies. This results from the fact that fluid cannot support any shearing stress" (Hsieh, 1979).

Raleigh and others clarify this direct impact that injecting wastewater has on stressed fractures given its inability to support any shearing stress:

> "The pressurized fluid enters a fracture and supports a part of the normal stress equivalent to the pressure of the fluid. As the fluid has no shear strength, the effective normal stress and the frictional resistance to sliding are lowered. If the fracture is subject to shear stress greater than the product of this effective normal stress and the coefficient of friction, the rocks will slip and generate an earthquake" (Raleigh et al., 1976).

Pore Pressure and Induced Seismology

Finally, elevating the pore pressure of the fluid in the rock can readily lead to seismic events given the proper conditions, like a stressed fault in contact with pressurized, migrating liquid. As the measure of the pressure of the fluid in the rock's pores and fractures, pore pressure is equal to the difference between applied normal stress and effective normal stress (Ellsworth, 2013). Thus as pore pressure increases, the effective normal stress will decrease. This effective normal stress can also be understood as the frictional resistance against the shearing stress along the fracture plane (Hsieh, 1979). If there is a sufficient enough increase in fluid pressure such that the shearing stress overcomes frictional resistance, the fault will slip and result in an earthquake. This is known as the Hubbert-Rubey mechanism, named after the findings in their seminal 1959 *Geological Society of America Bulletin* study "Role of fluid pressure in mechanics of overthrust faulting," as elucidated by Paul Hsieh:

> "The original work of Hubbert and Rubey (1959) actually concerns the role of pore pressure in the mechanics of overthrust faulting. They introduced the concept of rock movements caused by a Mohr-Coulomb-type failure in a fluid-filled rock environment. This concept was first cited by Evans (1966) in his paper on injection–earthquake relationship and subsequently gained wide acceptance as the mechanism through which injection has caused the earthquakes." (Hsieh, 1979)

In his "A review of theories of mechanisms of induced seismicity" that was published in *Engineering Geology*, Kisslinger relates that fluid injection induced earthquakes "are adequately explained" by a combination of the concept of effective pressure in a water-filled porous mechanism and the Coulomb-Mohr failure criterion, which embodies the three factors and their interrelationship that determines whether or not a particular fracking wastewater injection well will induce earthquakes (Kisslinger, 1976). Kisslinger further concludes that reservoir-related earthquakes, like those caused by fluid injection in bore holes, are induced by the same mechanisms, but in light of the lower injection pressures, "additional physical or chemical effects of the water on the materials may play an important role, [such as] a weakening of the materials in old fault zones by the introduction of water or static fatigue in silicate rocks due to stress corrosion (Kisslinger, 1976).

How to Turn On and Turn Off Earthquakes: The Parameters of Induced Seismology

Now that it has been clarified what events have to transpire in subterranean realms for earthquakes to be induced by fracking wastewater disposal, the question then becomes *how do these mechanisms relate to specific surface behaviors*? The things that we do above ground that directly impact what happens not only 13,000 feet below the surface, but beneath those sedimentary layers in the Precambrian crystalline basements where faults lie within impervious rock formations.

Davis and Frohlich, in their 1993 *Seismological Research Letters* study "Did (or will) fluid injection cause earthquakes? Criteria for a rational assessment," provide us with a starting point by establishing criteria through which one can determine whether or not a given earthquake was induced by wastewater disposal (Davis & Frohlich, 1993). These criteria "include proximity to injection wells, a change from background seismicity, and a correlation with wastewater injection parameters" (Keranen et al., 2013). These parameters related to wastewater injection referred to by Keranen and others, all of which are ultimately controlled by decisions made and actions taken by the deep-well injection companies on the surface, include fluid pressure, total fluid volume, and rate of fluid injection. As noted by William Ellsworth, "the physical connection between operational parameters such as injected volume" and fluid pressure can be complex (Ellsworth, 2013).

Fluid Pressure: Inducing Seismology By Exceeding Critical Value

The discovery by David Evans published in his 1966 *Geotimes* study, which led to speculations that earthquakes might be controllable, was that the subterranean high-pressure injection of fluid was responsible for the triggering of earthquakes at the Rocky Mountain Arsenal near Denver, Colorado in the early to mid 1960s. While earthquakes were being induced by the injection of pressurized wastewater into stressed rock formations, the reduction in fluid pressure caused a sharp decrease in frequency of seismic activity (Raleigh et al., 1976). A 1972 *Tectonophysics* study by Healy and others entitled "Prospects for earthquake prediction and control" more explicitly expressed this understanding and laid further groundwork for experimentally testing this hypothesis that, "Changes in fluid pressure may control timing of seismic activity and make it possible to control natural earthquakes by controlling variations in fluid pressure in fault zones" (Healy, et al., 1972).

Raleigh, Healy and Bredehoeft's landmark 1976 *Science* study "An Experiment in Earthquake Control at Rangely, Colorado" did demonstrate the capacity to turn on and turn off earthquakes and "established the correlation between fluid pressure and earthquakes beyond reasonable doubt," that they concluded the "control of the San Andreas fault could ultimately prove to be feasible." However, despite these earth-shattering revelations, perhaps the most important takeaway from these experiments was that, "successful prediction of the approximate pore pressure required for triggering of earthquakes according to the Hubbert-Rubey theory was possible" (Raleigh et al., 1976), as demonstrated by experimental verification of theoretical projections.

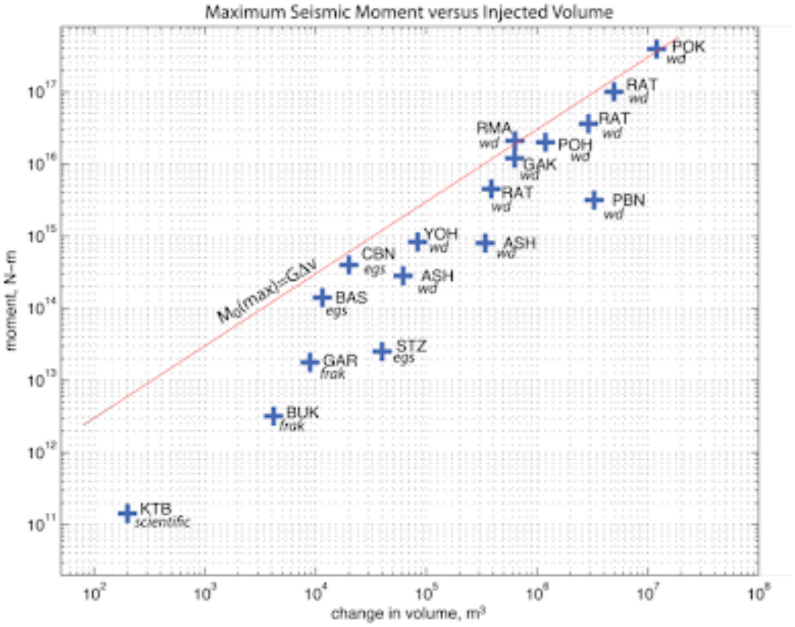
Predicting Earthquake Behavior, Controlling Earthquakes By Manipulating Fluid Pressure

Utilizing the Mohr-Coulomb failure criterion in applying the Hubbert-Rubey theory, Raleigh and colleagues projected that 257 bars (25.7 MPa) would be the Rangely site's critical fluid pressure. The critical fluid pressure, the pressure required to trigger an earthquake, is governed by the equation:

$\dagger_{crit} = \mu(S_n - P_c)$, with

$\dagger_{crit}$ = shear stress at failure point,
μ = coefficient of static friction of the rocks,
S_n = effective normal stress, and
P_c = critical fluid pressure that induces seismicity.

"The fluid pressure required to trigger earthquakes on preexisting fractures" was experimentally tested against the theoretical



projections through use of “laboratory measurements of the frictional properties of the reservoir rocks and an in situ stress measurement made near the earthquake zone” (Raleigh et al., 1976).

Experimental results, which were obtained by varying fluid pressure through the process of “alternately injecting and recovering water from wells that penetrated the seismic zone” (Raleigh et al., 1976), demonstrated that when the injection wells were subjected to fluid pressures above 257 bars the earthquake frequency increased, and when the fluid pressure was less than 257 bars the earthquakes subsided. The idea is that for any given injection well and pre-existing fault situation a critical fluid pressure can be determined, such that “we may ultimately be able to control the timing and the size of major earthquakes […] wherever we can control the fluid pressure in a fault zone” in relation to that critical fluid pressure (Raleigh et al., 1976).

Hsieh and Bredehoeft (1981), in an expansion of Hsieh’s 1979 master’s thesis (Hsieh, 1979), analyzed the Rocky Mountain Arsenal injection wells and earthquakes in similar fashion, utilizing Hubbert-Rubey theory to identify the fluid pressure critical value, “the pressure build-up above which earthquakes occur” (Hsieh, 1979). Their conclusion was that, “At the Rocky Mountain Arsenal near Denver, earthquakes occurred within the crystalline basement when the fluid pressures were raised over 320 m above hydrostatic conditions [32 bars, 3.2 MPa] between a depth of about 0.7–7 km (Hsieh and Bredehoeft, 1981; Zhang et al, 2013). Another way to frame this is that the earthquakes were confined strictly to those parts of the reservoir where the pressure build-up exceeded 32 bars (Hsieh, 1979). According to Davis and Frohlich (1993), Hsieh and Bredehoeft’s breakthrough was that they were “able to explain the spatial and temporal extent of seismic activity in Denver in terms of the flow of fluids along a permeable semi-infinite rectangular region which approximately contained the activity.”

Total Injected Fluid Volume and Maximum Earthquake Magnitude

The relationship between total fluid volume injected and induced seismology has been noted by many, whether it is the “qualitative correlation between earthquake rates and the injected volume” that has served as a tool for investigating the triggered earthquake phenomena (Oprsal and Eisner, 2013), or the case history-driven evidence suggesting a connection between the total volume of injected wastewater and the maximum induced earthquake magnitude (Hayes, 2012). The U.S. Geological Survey’s Art McGarr has compiled the data from these case histories and reports from fracking, waste disposal and geothermal induced seismic events, and has graphed Total Injected Volume vs. Maximum Earthquake Magnitude for 17 different cases of demonstrated fluid disposal triggered earthquakes (Holland and Keller, 2012; Verdon, 2013a; Verdon, 2013b):

Total Gal. Injected (thousands)	Magnitude Richter Scale	Location
53	1.4	Bavaria Germany (KTB)
1,057	2.3	Blackpool, England (BUK)
2,325	2.8	Garvin County, Oklahoma (GAR)
3,170	3.4	Basel, Switzerland (BAS)
9,774	3.7	geothermal at CBN
10,567	2.9	Soultz, France (STZ)
15,850	3.6	Ashtabula, OH (ASH)
21,134	3.9	Youngstown, Ohio (YOH)
89,818	3.8	Ashtabula, OH (ASH)
103,026	4.4	Raton Basin, Colorado (RAT)
158,502	4.6	Guy, Arkansas (GAK)
158,502	4.7	Rocky Mountain Arsenal (RMA)
766,093	5.0	Raton Basin, Colorado (RAT)
845,344	4.3	Paradox Basin, Colorado (PBN)
1,320,850	5.3	Raton Basin, Colorado (RAT)
3,170,040	5.7	Prague, Oklahoma (POK)

While “McGarr found a relationship between the maximum magnitude of induced earthquakes and the total volume of fluid injected into a site” (Balcerak, 2013), James Verdon reminds us that the McGarr model “is only empirical, there is no real physics behind it” (Verdon, 2013a). McGarr’s model does, however, create an interesting framework for further theoretical and experimental work, while also leading to the derivation of the McGarr equation for injection-induced seismicity:

$M_0(\max) = G\Delta v$, with

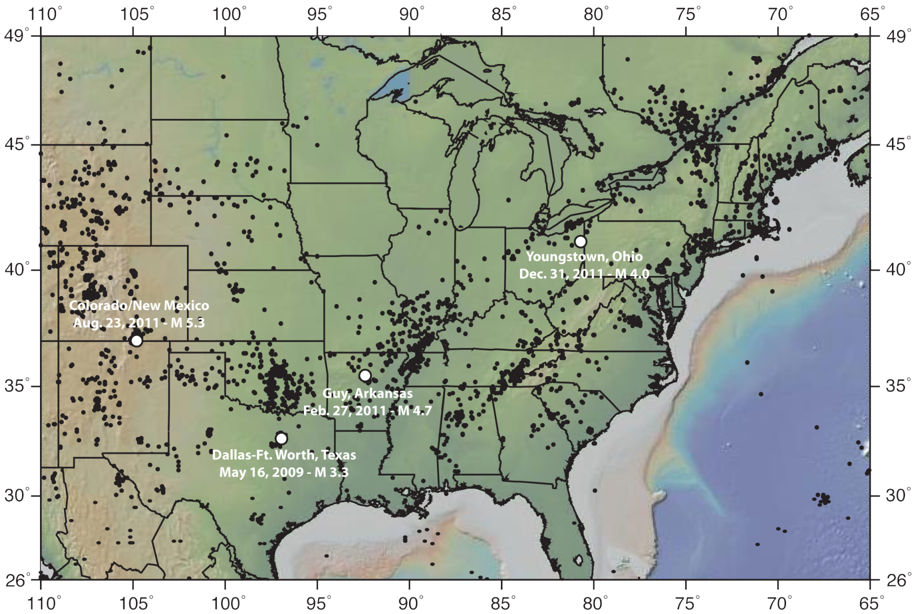
$M_0(\max)$ = magnitude of largest seismic moment,
G = shear modulus of rock
(ratio of shear stress to shear strain), and
Δv = total volume of fluid injected.

Despite potential shortcomings, Verdon does admit that, “In the meantime, we are left with the empirical McGarr equation as our main guide” (Verdon, 2013a). He also makes certain to clarify: “It should of course be remembered that the McGarr equation does not tell you the maximum magnitude you will get in an operation. […] The McGarr line tells you the maximum magnitude you could get if you are very unlucky” (Verdon, 2013a). While McGarr continues to clarify the undeniable connection between the total injected fluid volume and the potential maximum magnitude of induced earthquakes, he does not find the rate of fluid injection to impact the magnitude of triggered earthquakes, but rather he found “that the rate of injection of fluid influences the frequency of induced earthquakes” (Balcerak, 2013).

Rate of Fluid Injection and the Work of Cliff Frohlich

A third surface-controlled parameter that can impact fracking wastewater disposal induced seismicity is that of rate of fluid injection. While the rate of fluid injection and withdrawal played role in the Rangely, Colorado earthquake control experiments (Healy, et al., 1972), few scientists outside of Cliff Frohlich are investigating what he has observed to be a relationship between high rates of fluid injection and induced seismicity. From varies studies of the Barnett Shale play in Texas, Frohlich has found that injection wells nearest induced earthquake groups consistently reported maximum monthly injection rates in excess of 6.34 million gallons (24,000 cubic meters) of fluid, “and generally these injection rates had been maintained for a year or more prior to the onset of earthquake activity” (Frohlich, 2012).

While Frohlich has indicated in interviews that he is very much interested in pursuing this line of inquiry in other fracking wastewater injection regions (Choi, 2012), his own studies have already indicated that other faulted areas demonstrate different maximum monthly injection rates required to induce earthquakes, such as a fluid injection rate of 9.5 to 12.7 million gallons (32,000 to 48,000 cubic meters) per month in the case of Paradox Valley, Colorado (Frohlich et al, 2010). While there is still a lot of research and experimentation required to clarify the precise role of the three surface parameters of fluid pressure, total fluid volume, and rate of



fluid injection in triggering earthquakes, William Ellsworth concurs that experimental results distinctly suggest that these factors all "may be a predictor of seismic potential" (Ellsworth, 2013).

Conclusion

The mechanisms that underlie fracking wastewater disposal induced earthquakes have been clarified and verified since 1966, making the Hubbert-Rubey theory just a year younger than the theory of plate tectonics and its general acceptance. By capturing the interrelationships between primary earthquake inducement factors that include effective normal stress, shear stress and pore pressure, they set the stage for a couple of decades worth of rich experimentation. All of which became nearly forgotten until fracking industrialization's rude awakening, a literal shaking the foundations of where we work, where we shop and where we live. Luckily, "after a decades long lull in triggered quake studies, researchers are playing catch-up with the latest round of temblors" (Kerr, 2012). And so, in the spirit of existential philosopher Martin Heidegger's conception of truth, we find ourselves in the process of *revealing that which had been concealed*.

One of the great concerns of many of the seismologists and geologists working on this issue is the reality of the earthquake domino effect that have been observed as a result of wastewater injection-induced seismicity. University of Oklahoma seismologist Katie Keranen relates this as the operative scenario in the Prague, Oklahoma magnitude 5.7 earthquake that struck on November 6, 2011: "We had one fault-plane go, a second one, and then a third one. They ruptured in sequence" (Behar, 2013). Lamont-Doherty Earth Observatory seismologist Geoffrey Abers elucidates, "the amount of wastewater injected into the well was relatively small, yet it triggered a cascading series of tremors that led to the main shock" (The Earth Institute, 2013).

This is also of great concern to those potentially impacted individuals who live in Southern Illinois, existing between two active seismic zones, the New Madrid and the Wabash. With Southern Illinois facing the promise of mass fracking industrialization and its associated toxic and radioactive wastewater in need of disposal in deep-injection wells, it is not lost on many experts the danger that even small earthquakes can pose in this active seismic region. Geoffrey Abers acknowledges that, "the risk of humans inducing large earthquakes from even small injection activities is probably higher" than previously thought (The Earth Institute, 2013). A study conducted by the University of Illinois Mid-America Earthquake Center in 2008 projected that if an earthquake the magnitude of the quakes that hit near New Madrid during 1811-1812 were to strike today, "there would be 3,500 fatalities, 2.6 million people without electricity and $300 billion in direct economic losses. Bridges, docks, highways and water infrastructure would be in shambles" (IEMA, 2013).

If mass fracking industrialization is to take hold of Southern Illinois, a land amidst two active seismic zones, then higher intelligence must be allowed to govern this process, its regulations, and their application. Stanford University geophysicist Mark Zoback answers this call by providing an empirically derived practical framework for reducing the probability of induced seismicity, with five straightforward steps:

(1) It is important to avoid injection into active faults and faults in brittle rock.

(2) Formations should be selected for injection (and injection rates should be limited) to minimize pore pressure changes.

(3) Local seismic monitoring arrays should be installed when there is a potential for injection to trigger seismicity.

(4) Protocols should be established in advance to define how operations will be modified if seismicity is triggered.

(5) Operators need to be prepared to reduce injection rates or abandon wells if triggered seismicity poses any hazard (Zoback, 2012).

These five steps provide both the state (in form of regulators) and industry (in the form of operating companies) with a structure for reducing the risks involved in fracking wastewater disposal via deep-injection wells and the induced earthquakes that can accompany their utilization.

Brent Ritzel received his BA in Philosophy from Northwestern University in 1990 and is currently working on his master's thesis PROJECTED TOTAL COSTS OF ROADWAY DEGRADATION DUE TO PROPOSED FRACKING INDUSTRIALIZATION OF SOUTHERN ILLINOIS *for a Master of Public Administration degree at Southern Illinois University Carbondale, expected completion May 2014.*

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