Potential risks of fault reactivation associated with the production of shale gas by hydraulic fracturing

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Abstract

As an unconventional natural gas, shale gas has increasingly attracted attention around the world. Horizontal drilling and hydraulic fracturing are the primary technologies, which make the extraction of tightly bound natural gas from shale formations economically feasible. However, their potential environmental effects remain controversial, especially those related to water pollution. Among various possibilities, the conductive faults should be treated as the focus of attention because they serve as major pathways for gas or contaminant discharge to shallow groundwater. During the hydraulic fracturing, a critically stressed fault can be reactivated because of the increased pore water pressure and the decreased effective stress on the fault planes. In general, fault reactivations are highly related with seismic events during and post hydraulic fracturing operation, and this correlation has been record in many different places around the word. Although there is lack of sound scientific filed observations and peer-reviews articles on the effects of fault reactivation on shallow groundwater quality, the probability of causal relationship is high. In this study, we reviewed the seismicity induced by shale gas development and other fluid injection engineering. Mechanism of fault reactivation associated with the production of shale gas by hydraulic fracturing was discussed and the formation of the transport pathways of contaminants was depicted to help manage the environmental risks in the production.

Keywords: shale gas, hydraulic fracturing, fault reactivation, water pollution

1. Introduction

The presence and application of the horizontal drilling and hydraulic fracturing technologies make the extraction of unconventional sources of gas economically feasible. Recently, there has been considerable attention focused on earthquakes associated with the hydraulic fracturing of shale gas formations (Rutqvist et al. 2013; Hummel and Shapiro 2013). Public attention to internal relations between earthquakes and fluid injection begin from early seismic events in the wastewater injection, geothermal energy development, enhanced oil recovery, and carbon capture and storage.

Fluid injection and hydraulic fracturing induced fractures and fault reactivation can provide permeable pathways for fluids at variety of scales. Public concerns about ground water contamination from hydraulic fracturing are prevalent because the hydraulic fracturing fluids are toxic mixtures, which consist of water, proppants, and chemicals. The amount of injected fluid that returned to the ground surface after hydraulic fracturing only 9% to 34% of the injected fluid (Alleman 2011). Although many investigations have been done to study the hydraulic connectivity between the deep shale gas formation and the shallow drinking water aquifers, such as Osborn et al. (2011), Warner et al. (2012), Myer (2012), and Vidic et al. (2013), but still lack a strongly convinced evidence.

Mechanically, injection-induced seismicity and hydraulic fracturing induced seismicity share the same mechanics, which all involves the principle of effective stress and slip or failure of rock discontinuities on different scales. Elevated fluid pressure can change the stress state of the surrounding rock masses, especially the rock discontinuities on different scales.

Failures of the rock discontinuities are usually accompanied with microseismic activities. The larger the structure planes slip, the greater the magnitudes of the seismicity come into being. Seismic monitoring provides valuable data for assessing the earthquake potential of the injection or fracturing operations (Das and Zoback 2011; Frohlich 2012). In this study, the earthquakes induced by traditional fluid injection and hydraulic fracturing of the shale gas were re-evaluated and mechanisms of fault reactivation associated with the injection and production of shale gas by hydraulic fracturing was discussed. The factors that influence the fault reactivation in hydraulic fracturing were evaluated to help manage the environmental risks in the production.

2. Lessons from injection-induced earthquakes

Although it is known that long-term injection operation in the deep subsurface can induce earthquakes in some circumstance, it is still difficult to discriminate the man-made and natural tectonic earthquakes because of incomplete information on the initial stress state, geologic structure, hydrogeology, injection history, and the pressure changes surrounding the injection wells. Among the numerous cases of earthquakes that were likely induced by injection operations, several confirmed and well-documented cases are available to learn the pre-injection stress state, injection history, as well as the earthquake relations.

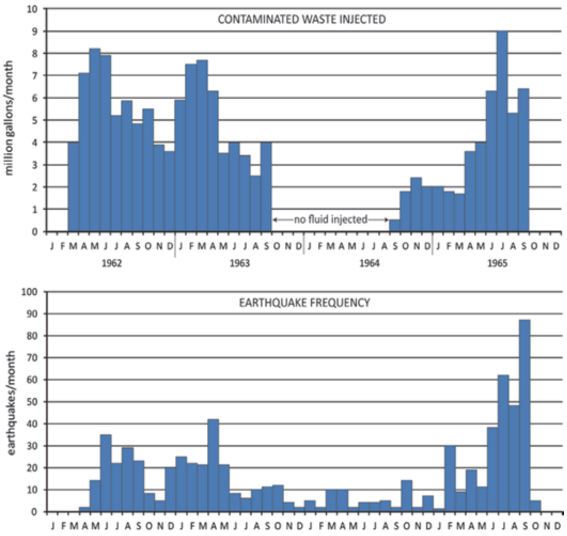

Fig. 1 Histograms showing relation between volume of waste injection and earthquake frequency in the Rock Mountain Arsenal well. Some of the earthquakes were sensible and about 13 of them with magnitudes larger than Mw 4.0 occurred during the above period. The maximum magnitude occurred with magnitude of Mw 4.8 in August 1967 (adapted from Evans (1966); Healy et al. (1968); McClain (1970); Hsieh and Bredehoeft (1981); National Research Council (2013)).

Among these injection-induced earthquakes, the most notable one was the US army's injection of fluid into a 12,000 ft deep well at the Rocky Mountain Arsenal approximately 6 miles northeast of the downtown Denver. Although the Denver had been previously considered to be in an area of low seismicity, more than 1,500 earthquakes were recorded between 1962 and 1967 because of the deep injection operations. As illustrated in Fig. 1, there was a significant relation between the volume of waste injection and the earthquake frequency. The farthest earthquake migrated about 10 km from the injection well that tracked a critical pore pressure front of 3.2 MPa. The Rocky Mountain Arsenal earthquake illustrates that the diffusion of pore pressure within an origin fault zone can initiate earthquakes many kilometers from the injection wells (Ellsworth 2013). That is, the earthquakes can delay several months or even many years after injection.

At Paradox Valley, the fluid-injection project has been under way since 1996 in order to reduce salinity in the Colorado River. Between 1996 and 2014, more than 5,700 earthquakes were recorded around 12 km of the injection point where only 3 tectonic earthquakes occurred within 15 km of the injection well during 1985 and 1996. The maximum earthquake was Mw 4.3 in May 2000. As illustrated in Fig. 2, a significant relation existed between the volume of fluid injection and the earthquake frequency. The paradox Valley experience illustrates that long-term, high-volume injection can lead to the continued expansion of the activated area and triggering of earthquakes many kilometers from the injection point more than 15 years after the initial earthquake occurrence (Ellsworth 2013).

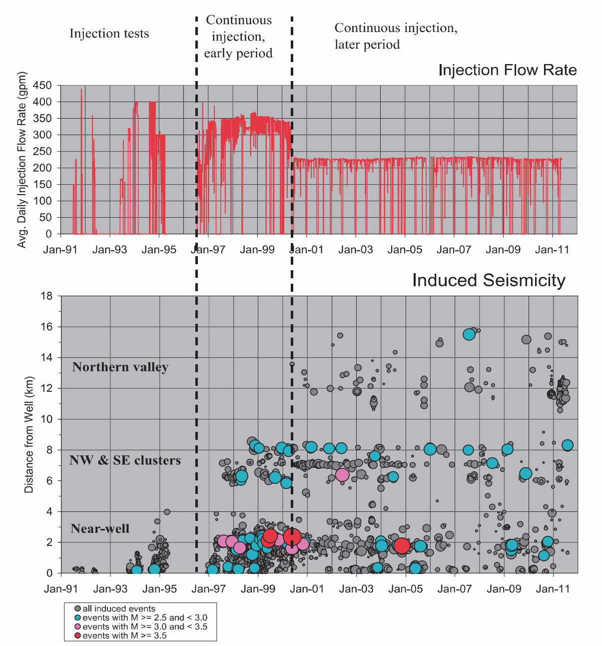

Fig. 2 Histograms showing relation between volume of waste injection and earthquake frequency in the Paradox Valley (adapted from Block (2011); National Research Council (2013)).

Similarly, other long-term injection operations, such as geothermal injection in Geysers (USA) and Basel (Switzerland) (Majer et al. 2000), oil and gas recovery in Rongchang (China) (Li et al. 2008), Zigong (China) (Li et al. 2013), and potential sources in areas where the geologic conditions are favorable for the occurrence of earthquakes.

3. Earthquakes induced by hydraulic fracturing

Hydraulic fracturing is an essential technology that involves the injection of fluid under pressure to create network of open fractures in reservoirs especially in the ultralow permeable shale gas reservoirs, thereby increasing the permeability of rock formations. In general, the horizontal drill wells were drilled several kilometers within the reservoirs and tens of thousands of cubic meters of fracturing fluid were pumped into the shale reservoirs with extremely high pressure to create tensile fractures. The aforementioned injection-induced earthquakes are a good analog for the potential for earthquakes to be triggered by hydraulic fracturing.

Recently, several cases have been reported in which earthquakes large-than-usual seismic events were associated directly with the hydraulic fracturing of the shale gas reservoirs. One of the most notable cases that has been documented and confirmed in which hydraulic fracturing induced felt earthquake was occurred in Blackpool, England, in 2011 (De Pater and Baisch 2011). Site investigation recorded two prominent seismic events of magnitude Mw 2.3 and Mw 1.5, which were induced by injection of a large volume of injection fluid into a fault zone that has not been previously found in the early geological prospecting. In the Eola Field of Garvin County, Oklahoma, a series of felt seismic activity that ranged in magnitude from 1.0 to 2.8 were recorded within 5 km of from the well due to hydraulic fracturing operation. In addition, an unusual series of seismic events were recorded in the Hom River Basin of British Columbia during hydraulic fracturing in adjacent to a pre-existing fault (Ellsworth 2013). In this instance, there were 21 seismic events with Mw 3.0 and the larger were recorded and the maximum was Mw 3.6. However, the quality of the even locations was not adequate to full establish a direct causal link to hydrofrac treatment. Beyond that, there are some other examples of hydrofrac induced seismic events (Mw<2). However, all these seismic events are small and which can still be classified as mic-seismicity. In other words, the present process of hydraulic fracturing for shale gas recovery does not pose a high risk for production and public safety.

4. Mechanics of induced fault reactivation

Both the mic-seismic events and felt earthquakes are a performance of release of elastic strain energy stress release of rock discontinuities on different scales. Under normal circumstance, the structural planes or fault surface are remain locked because of frictional resistance on the structural planes caused by the in situ stresses. The fault slips when the shear stress is large enough to overcome the friction forces, resulting in a seismic event. The fluid injection or the hydraulic fracturing can increase the pore pressure in the rock discontinuities, which act to counteract the normal stress on the structural planes and result in a decrease in the frictional force. Once initiated, frictional resistance drops and seismic waves radiate away.

The mechanisms are illustrated in the schematic maps of Figs. 3 and 4. In the macroscopic view, the rock masses slip along an entire fault plane and release the elastic strain energy. In the microscopic view, rock bridge failure among multi-cracks caused local slip damage of the fault, rather than one large reactivation along the entire fault plane.

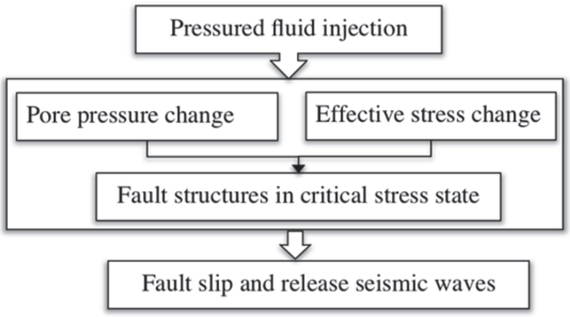

Fig. 3 Schematic map of the mechanics of fault reactivation induced by fluid injection.

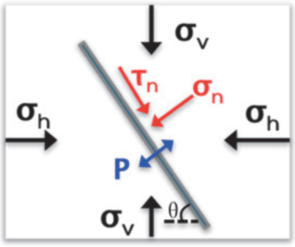

Fig. 4 Schematic map of the stressed state of a fault plane. The normal and shear stresses acting across the fault depend on the vertical and horizontal stress and the fault inclination.

Mechanically, fluid injection/hydraulic fracturing is a dynamic mechanical process. Fluids are pumped into the well under high pressure to open the existing fractures or initiate new fractures. The direct change of pore water pressure resulting from fluid injection can generate significant changes in effective stresses.

The change of effective stress is related to the pore water pressure change and the total stress changes can be expressed as follows (Soltanzadeh and Hawkes 2009):

$$\Delta\sigma_{ij} = \Delta\sigma'_{ij} + \alpha\Delta P_f \delta_{ij} \qquad (1)$$

Where $\Delta\sigma_{ij}$ is the total stress changes, $\Delta\sigma'_{ij}$ is the effective stress, α is Biot's coefficient, ΔP_f is the pore pressure changes, and δ_{ij} is the Kronecker delta.

For the convenient of poroelastic analysis, we define the stress arching ratio γ_{ij}, which is the ratio of the $\Delta\sigma_{ij}$ to the ΔP_f within the rock mass.

$$\gamma_{ij} = \Delta\sigma_{ij} / \alpha\Delta P_f \qquad (2)$$

As for a fault in which the initial and induced stress changes in the vertical and horizontal are principal stresses, the induced horizontal and vertical effective stress changes within the rock mass can be expressed as follows:

$$\Delta\sigma_h' = -\left(1-\gamma_h\right)\alpha\Delta P_f \qquad (3)$$

$$\Delta\sigma_v' = -\left(1-\gamma_v\right)\alpha\Delta P_f \qquad (4)$$

In the two dimensional case, the shear stresses (τ) and normal stresses (σ_n) on a fault plane can be solved by a subsection method.

$$\begin{aligned}\tau &= \frac{1}{2}(\sigma_z - \sigma_x)\sin 2\theta + \tau_{xz}\cos 2\theta \\ &= \frac{1}{2}(S_v - S_{\mathrm{h}} - \alpha\Delta P_f(2-\gamma_v-\gamma_h)\sin 2\theta + \tau_{xz}\cos 2\theta\end{aligned}$$

(5)

$$\begin{aligned}\sigma_n &= \sigma_x\cos^2\theta + \sigma_z\sin^2\theta + 2\tau_{xz}\cos 2\theta \\ &= (S_h + \Delta\sigma_h)\cos^2\theta + (S_v + \Delta\sigma_v)\sin^2\theta + 2\tau_{xz}\cos 2\theta\end{aligned}$$

(6)

Where θ is the dip angle of the fault plane, S_v and S_{h} are the vertical and horizontal geo-stress, respectively. In an injection scenario, the likelihood of fault reactivation can be evaluated through the Coulomb Failure Criteria:

$$\tau = C + \mu(\sigma_n - P_f) \qquad (7)$$

Where C is the cohesive strength of the fault plane; and μ is the coefficient of friction in the fault plane. The coefficient of friction is in the range 0.6-0.85 (Byerlee, 1978). Using the chart method in Fig. 7, all possible orientations of faults lie within the shade area. The horizontal distance between any orientation and the failure envelope is used to evaluate the propensity of the plane to failure.

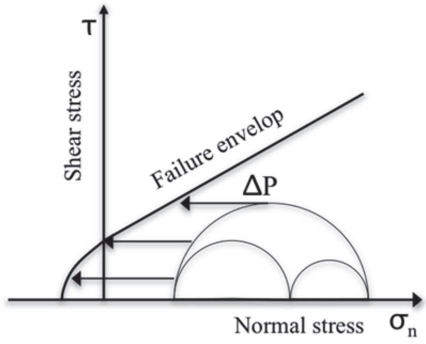

Fig. 5 Three-dimensional Mohr diagram with composite Griffith Coulomb failure envelop (revised from Mildren et al. (2002)).

The change in Coulomb Failure Stress can be evaluated as (King et al. 1994):

$$\Delta CFS = \Delta\tau - \mu\Delta\sigma_n' \qquad (8)$$

Where $\Delta\tau$ and $\Delta\sigma_n$ are shear stress and effective normal stress in a fault plane. Thus, the fault reactivation factor (λ) can be defined and used to evaluate the characterization of reactivation (Soltanzadeh and Hawkes 2009). In addition, the slip tendency of the fault elements can be calculated through a ratio of shear to the effective normal stress

(T_s).

$$\lambda = \Delta CFS / \alpha \Delta P_f \tag{9}$$

$$T_s = \tau / (\sigma_n - P_f) \geq \mu_{fault} \tag{10}$$

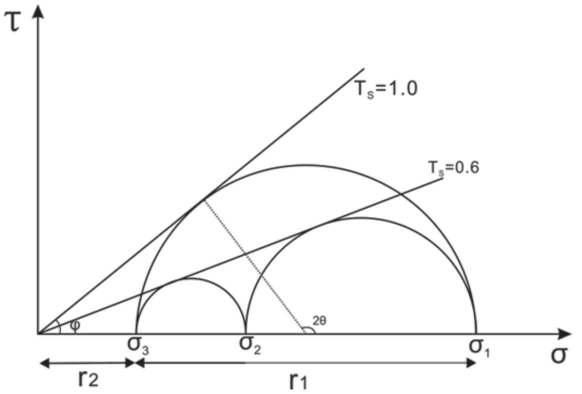

Fig. 6 Sketch of normalized slip tendency in relation to the Mohr diagram. Principal stresses σ_1, σ_2, and σ_3, can be expressed in terms of unknown parameters r_1 and r_2.

In addition, the slip tendency of a fault plane can be visually represented by a graphic method. As illustrate in Fig. 6, the normal stress on the fault plane can be drawn in the three-dimensional morh's stress circle. Connect the origin point and the normal stress point to form a straight line. The slope of the line represents the degree of risk for the fault slip. Specifically, the larger the slope of the line, the higher risk of the fault occurs slip damage.

In the critical state of a fault reactivation, the upper limit and lower limit of the pore pressure in the fault plane can be back calculated under the condition that the friction coefficients of the fault planes are specified as the minimum and maximum threshold.

$$P_{c1} = \frac{r_1}{2\sin\varphi}\begin{bmatrix} ((1+\sin\varphi)l^2 + ((1-2\delta)\sin\varphi+1)m^2 \\ +(1-\sin\varphi)n^2) \\ -\left[\delta^2 l^2 m^2 + (1-\delta)^2 m^2 n^2 + n^2 l^2\right]^{1/2} \end{bmatrix}$$

(11)

$$P_{c2} = \frac{r_1}{2\sin\varphi}\begin{bmatrix} ((1+\sin\varphi)l^2 + ((1-2\delta)\sin\varphi+1)m^2 \\ +(1-\sin\varphi)n^2) - \\ 0.6\left[\delta^2 l^2 m^2 + (1-\delta)^2 m^2 n^2 + n^2 l^2\right]^{1/2} \end{bmatrix}$$

(12)

For a fault located in the influence area of the hydraulic fracturing, the critical pore pressure ranges between the upper and lower threshold of the pore pressure ($P_{c1} \leq P_c \leq P_{c2}$).

The injection or hydraulic fracturing fluid can greatly decrease the effective normal stress and cohesive force on the fault surface, thus decreasing the shearing strength of the fault. When the pore pressure comes to the critical state, the fault occurs slip failure. Sometimes, the injection fluid can migrate several thousands feet within a fault. More importantly, the change of pore pressure tends to cause local slip damage along oblique factures in the fault zone, rather than a larger scale reactivation event along the entire fault surface. Fault reactivation could enhance the permeability of the rock mass and provide flow pathways for gas or fracturing fluid discharge to shallow ground water.

5. Influencing factors of fault reactivation

Investigations show that many factors influence the initiation and extent of a fault reactivation when the fault is stimulated by hydraulic fracturing operation. Nevertheless, these factors could be classified into two broad categories.

Geomechanical parameters

- In situ crustal stress
- Relative position of the fault
- Fault mechanics
- Permeability of fault zone
- Pore water pressure

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Hydraulic fracturing parameters

- Injection depth
- Injection rate
- Injection duration
- Injection volume

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The interaction and triggering mechanism of these factors is a complex issue. But in general, when a critical stress fault located in the optimal position and direction of the injection region, a minor change of pore water pressure can destroy the local balance of friction on the fault plane, resulting slip damage and seismic events. In ideal circumstances, the increase in injection rate and net injection volume can greatly stimulate the reactivation of faults and other scales of rock discontinuities. As illustrated in Fig 7, the seismicity shows three forms. First, the number of seismic events of Mw 1.5 and greater have increased from almost none in the 1960s to 112 in 1975 and then to 1,384 in 2006. Second, the annual number of earthquakes of Mw 3.0 and greater is shown along the bottom of the graph. By 1985, these events occurred 25 annually. Third, seismic events of M4.0 and greater are shown neat the top. Such events have been recorded about one to three of per year since1972. The maximum magnitude of earthquake was Mw 4.67 in May 2006 (Smith et al. (2000); Majer et al. (2007)).

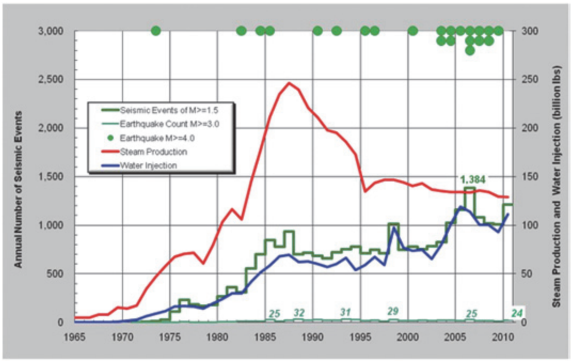

Fig. 7 Histograms showing the seismicity induced by water injection in the Geysers for geothermal energy production (adopted from Smith et al. (2000); Majer et al. (2007); National Research Council (2013)).

6. Conclusions

Fault slip is highly related with seismic events during and post injection/hydraulic fracturing operation, and this correlation can be identified as an evidence for fault reactivation. Injection/hydraulic fracturing fluid can greatly decrease the effective normal stress on the fault surface, thus decreasing the shearing strength of the fault plane. When the shear stress is large enough to overcome the friction force, the fault slips, resulting in seismic events.

Pressured fluid tends to cause failure of multi-cracks and resulting in local slip damage, rather than one large-scale slip/reactivation along the entire fault plane. However, even a minor slip failure of fault, it could increase the permeability of the fault zone and may create new flow pathways for upward fluid migration.

There are many factors influence the performance of fault reactivation. The geomechanical properties of the fault play a decisive role. The injection parameters are the triggering factors. In general, the increase in injection rate and net injection volume can greatly stimulate the reactivation of a critical stress fault or other rock discontinuities on different scales.

Acknowledgements

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References

Alleman, D. (2011): Water used for hydraulic fracturing: Amounts, sources, reuse, and disposal. In hydraulic fracturing of the Marcellus Shale, National Ground Water Association short course. Baltimre, Maryland.

Block, L. (2011): Paradox Valley Deep Disposal Well and Induced Seismicity. Presentation to the National Research Council Committee on Induced Seismicity Potential in Energy Technologies, Dallas, TX, September 14.

Byerlee, J. (1978): Friction of rocks. Pure and Applied geophysics, Vol. 116, No. 4-5, pp. 615-626.

Das, I. and Zoback, M.D. (2011): Long-period, long-duration seismic events during hydraulic fracture stimulation of a shale gas reservoir, The Leading Edge, Vol. 30, No. 7, pp. 778-786.

De Pater, C.J. and Baisch, S. (2011): Geomechanical Study of Bowland Shale Seismicity—Synthesis Report. Prepared for Cuadrilla Resources. November 2. Available at http://www.cuadrillaresources.com/wp-content/uploads/2012/02/Geomechanical-Study-of-Bowland-Shale-Seismicity_02-11-11.pdf (accessed June 2012).

Ellsworth, W.L. (2013): Injection-induced earthquakes, Science, Vol. 341, No. 6142, pp. 1225942-1-1225942-7.

Evans, D.M. (1966): The Denver area earthquakes and the Rocky Mountain Arsenal disposal well, Mountain Geologist, Vol. 3, No. 1, pp. 23-26.

Frohlich, C. (2012): A survey of earthquakes and injection well locations in the Barnett Shale, Texas, The Leading Edge, Vol. 31, No. 12, pp. 1446-1451.

Healy, J.H., Rubey, W.W., Griggs, D.T. and Raleigh, C.B. (1968): The Denver earthquakes, Science, Vol. 161, No. 3348, pp. 1301-1310.

Hummel, N. and Shapiro, S.A. (2013): Nonlinear diffusion-based interpretation of induced microseismicity: A Barnett Shale hydraulic fracturing case study, Geophysics, Vol. 78, No. 5, pp. B211-B226.

Hsieh, P.A. and Bredehoeft, J.S. (1981): A reservoir analysis of the Denver earthquakes: A case of induced seismicity, Journal of Geophysical Research, Vol. 86, No. B2, pp. 903-920.

King, G.C.P., Stein, R.S. and Lin, J. (1994): Static stress changes and the triggering of earthquakes. Bulletin Seismological Society America, Vol. 84, No. 3, pp. 935-953.

Lei, X.L., Yu, G.Z., Ma, S.l., Wen, X.Z. and Wang, Q.

(2008): Earthquakes induced by water injection at ~3 km depth within the Rongchang gas field, Chongqing, China, Journal of Geophysical Research, Vol. 113, pp. 1-12.

Lei, X.L., Ma S.L., Chen, W.K., Pang, C.M., Zeng, J. and Jiang, B. (2013): A detailed view of the injection-induced seismicity in a natural gas reservoir in Zigong, southwestern Sichuan Basin, China, Journal of Geophysical Research, Vol. 118, 4296-4311.

Majer, E.L., Baria, R., Stark, M., Oates, S., Bonner, J., Smith, B. and Asanuma, H. (2007): Induced seismicity associated with enhanced geothermal systems, Geothermics, Vol. 36, pp. 185-222.

McClain, W.C. (1970): On earthquakes induced by underground fluid injection. ORNL-TM-3154. Oak Ridge, TN: Oak Ridge National Laboratory.

Mildren, S.D., Hillis, R.R and Kaldi, J. (2002): Calibrating predictions of fault seal reactivation in the Timor Sea, APPEA Journal, Vol. 42, pp.187-202.

Myers, T. (2012): Potential contaminant pathways from hydraulically fractured shale to aquifers, Groundwater, Vol. 50, No. 6, pp. 872-882.

National Research Council (2013): Induced Seismicity Potential in Energy Technologies, Aviable at: http://www.nap.edu/openbook.php?record_id=13355 (accessed May 2015).

Osborn, S.G., Vengosh, A., Warner, N.R. and Jackson, R.B. (2011): Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing, Proceedings of the National Academy of Sciences, Vol. 108, No. 20, pp. 8172-8176.

Rutqvist, J., Rinaldi, A.P., Cappa, F. and Moridis, G.J. (2013): Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs, Journal of Petroleum Science and Engineering, Vol. 107, pp. 31-44.

Smith, J.L.B., Beall, J.J. and Stark, M.A. (2000): Induced seismicity in the SE Geysers Field, California, USA, Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, May 28-June 10.

Soltanzadeh, H. and Hawkes, C. (2009): Assessing fault reactivation tendency within and surrounding porous reservoirs during fluid production or injection, International Journal of Rock Mechanics & Mining Science, Vol. 46, No. 1, pp. 1-7.

Vidic, R., Brantley, S., Vandenbossche, J., Yoxtheimer, D. and Abad, J. (2013): Impact of shale gas development on regional water quality, Science Vol. 340, No. 6134, pp. 1235009-1-1235009-9.

Warner, N.R., Christie, C.A., Jackson, R.B. and Vengosh, A. (2013): Impacts of shale gas wastewater disposal on water quality in Western Pennsylvania, Environmental science & technology, Vol. 47, No. 20, pp. 11849-11857.