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REVIEW

Induced seismicity: the potential hazard from shale gas development and CO_2 geologic storage

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ABSTRACT: We present an overview of the current status of unconventional energy development, particularly of shale gas, and underground CO_2 storage as a measure to mitigate greenhouse gas increase in the atmosphere. We review their potential to induce seismicity, which has caused debates among related energy enterprises, engineers, researchers, and environmental and public communities regarding their potential hazards. Studies show that fracking can be a problem in that it consumes abundant water, but the seismicity induced by fracking has not yet been observed to induce many felt earthquakes. However, massive wastewater injection, a part of the unconventional energy development process has caused *M*5.0+ earthquakes in the past as well as several recent and ongoing cases of induced seismicity. Large-scale CO_2 injection as a part of carbon sequestration efforts in the near future has a high risk of inducing large earthquakes. Therefore, injection operations related to both unconventional energy development and carbon sequestration should be optimized and managed to mitigate the likelihood of an induced seismic event.

Key words: induced seismicity, shale gas, hydraulic fracturing, wastewater injection, carbon capture and storage, CO_2 injection

1. INTRODUCTION

In the 21st century, human society faces two critical and closely related problems: securing energy sources and mitigating global warming. Without appropriately tackling these problems, we may not be able to sustain societal and economic development (Barnett, 2003; Asif and Muneer, 2007; Szuromi et al., 2007; Gislason and Oelkers, 2014). Since the onset of the industrial revolution, our consumption of fossil fuels has increased dramatically and now we have been very much dependent on the fossil fuels, including coal, oil, and gas in our daily life (Broecker et al., 1979; Dresselhaus and Thomas, 2001; Bose, 2010; Day et al., 2014; Kim et al., 2014).

The 21st century experienced unprecedented climate changes on a global scale. Although some contradicting arguments persist, the main cause of global warming is attributed to excessive or uncontrolled human consumption of fossil fuels, resulting in highly elevated levels of green-house gases, especially CO_2, in the atmosphere (Drake, 2000; Khandekar et al., 2005; Mann, 2014). To cope with this climate concern, a variety of measures have been implemented, including searching for alternative energy sources that emit less CO_2 than conventional fossil fuels and developing energy efficient devices, equipment, and buildings. In the interim, many have proposed capturing and storing produced CO_2 in the subsurface, a process known as carbon capture and storage (CCS), as a potentially significant piece of a carbon-neutral future (Paustian et al., 1998; Yamasaki, 2003; Lee, 2009; Kim et al., 2014).

Alternatives to conventional oil production include geothermal, wind, solar, biofuel, and, more controversially, nuclear energy. However, the expansion of nuclear power for supplying electricity has not been large since the Fukushima disaster demonstrated the danger of this type of energy source (Huenteler et al., 2012; Hong et al., 2013). A push toward utilization of greater renewable energy sources is occurring in many countries, including Korea, China, and Japan (Lee, 2009; Chen et al., 2014; Zhao et al., 2014). However, the proportion of renewable energy to total energy use is not high. One of the main reasons for this low proportion is that most renewable energy requires institutional or governmental subsidy for practical application at the present technology level (Lee, 2009; Murray et al., 2014). In addition, renewable energy may have limitations in meeting large energy demands as a primary energy supply.

Biofuels, produced from living organisms such as corn, sugarcane, and vegetables, are a potential significant renewable energy source, but the widespread adoption of biofuels has caused controversy over using a potential food source as a fuel (Elobeid and Hart, 2007; Srinivasan, 2009). Blending ethanol with gasoline and diesel is meant to reduce the emission of CO_2 from fossil fuel (Hill et al., 2006), but the blending percentage varies greatly among countries, from 10% in the U.S. (in the case of ethanol in gasoline; Westcott, 2007), 5% in Canada (by 2020), to no blending in Korea, and depends on institutional and societal conditions. In some cases, conventional energy enterprises strongly resist the introduction of biofuels because they expect that such measures will reduce their profits.

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Conventional energy companies have suffered from progressively increasing oil exploration and development costs, as many of the existing fields are being depleted (Sorrell et al., 2010). Therefore, energy companies have developed innovative technologies to scavenge the nearly depleted oil fields or to search for new alternative fuel sources. Unconventional energy sources such as shale oil, shale gas, and coal bed methane (previously impractical or uneconomic) have become a focus of their interest (Wang et al., 2014). As new technologies such as horizontal drilling and hydraulic fracturing (fracking) are developed, shale gas increasingly becomes an accessible "energy game changer", heralding the so-called shale revolution or energy revolution (Jaffe, 2010; Boersma and Johnson, 2012; Hughes, 2013).

The development of shale gas has been confronted with critical problems. The process of hydraulic fracturing has been blamed for excessive use of water, which is required to break shale formations to create permeable pathways for gas to flow (Guo et al., 2014). Fracking requires injection of, on average, 20 million liters of water into each well (Howarth et al., 2011). Should we sacrifice clean water for energy? Furthermore, fracking has caused debates regarding the contamination of shallow groundwater due to the injection of fracking fluid containing proppant and chemicals, and the release of methane, radioactive compounds and heavy metals (Manuel, 2010; Mooney, 2011; Gassiat et al., 2013; Simon, 2014; Flewelling and Sharma, 2015; Lefebvre et al., 2015). The situation is further aggravated by studies suggesting that massive wastewater injection wells, which dispose of wastewaters from the hydraulic fracturing process, can cause significant earthquakes (up to *M*6.0) (Ellsworth, 2013; Keranen et al., 2013, 2014). The state of Oklahoma, considered stable tectonically, is experiencing tremors (*M*3.0+) due to induced earthquakes, coincident with high-volume wastewater injection (Holland, 2013; Keranen et al., 2013, 2014).

The induced seismicity is not limited to wastewater injection (McGarr et al., 2015; Fig. 1); other activities of concern include underground CO_2 storage in carbon capture and storage (CCS) projects (Zoback and Gorelick, 2012; Hitzman, 2014; Verdon, 2014), deep drilled enhanced geothermal systems (EGS) (Majer et al., 2007; Giardini, 2009; Brodsky and Lajoie, 2013; Karvounis et al., 2014; Kuehn et al., 2014), and conventional oil and gas extraction (NAS, 2013). Like wastewater injection, injection of CO_2 or water can also cause felt (*M*3.0+) earthquakes (Lei et al., 2008). Thus, public concerns about these induced earthquakes can decelerate the practical application of energy technologies (NAS, 2013; Clarke et al., 2014).

The objectives of this paper are to present a brief overview

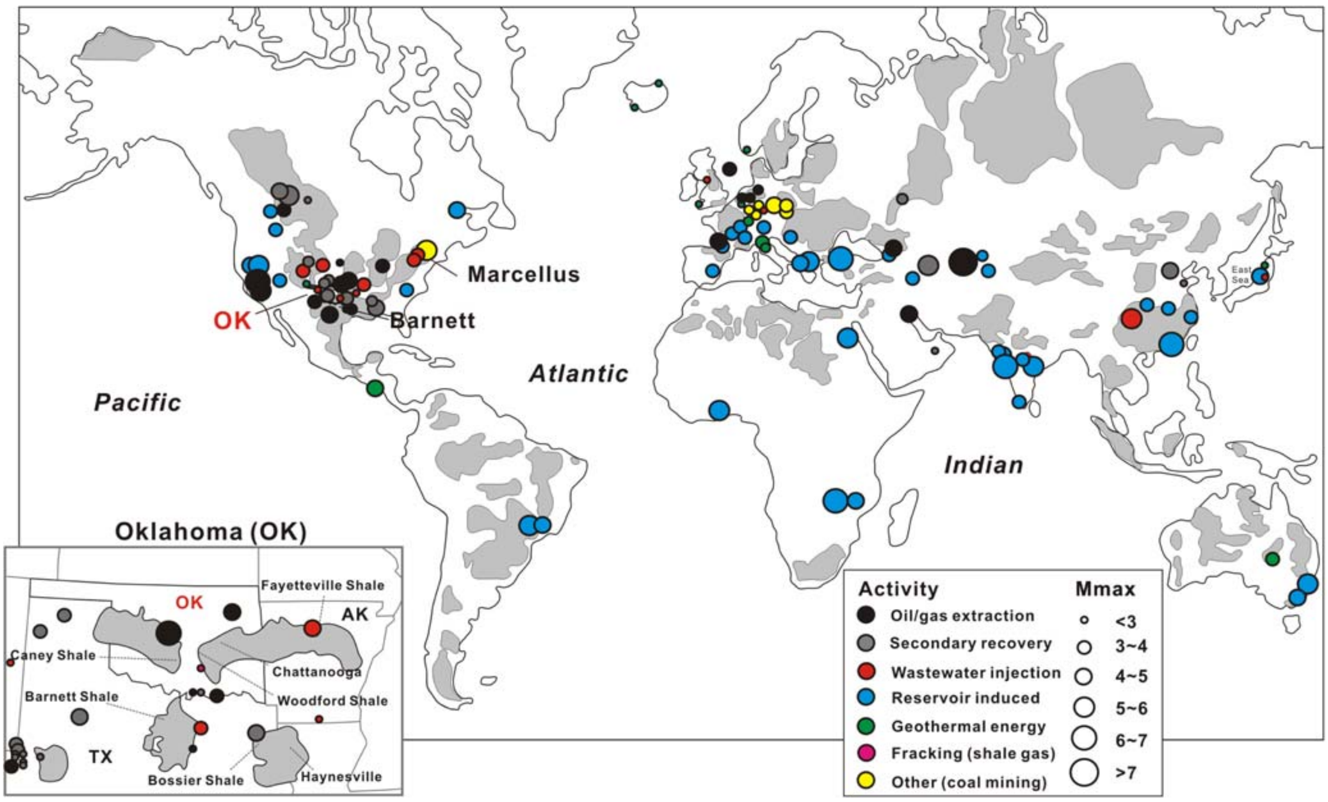

Fig. 1. Induced seismicity and assessed basins (light grey colored) with shale oil and shale gas formations in the world. The base figure and basin location data are from USEIA (2013). The inset map (location of Oklahoma and surrounding shale gas basins) is redrawn from USGS (2013). The induced seismicity data (reported until June 2012) are from NAS (2013).

of the current status of shale gas development and underground CO_2 storage in the world, and to subsequently review their potential to induced earthquakes as well as other related externalities. If the risks and costs are high, attention must be paid, and optimum operation is needed to secure the energy supply and the stored CO_2.

2. SHALE GAS DEVELOPMENT AND CARBON STORAGE

2.1. Shale Gas Development

Shale gas is natural gas, mostly methane, trapped within shale formations that act as a reservoir. In the past, shale gas was not technically or economically feasible, mainly because of the low permeability of the reservoirs (Jarvie et al., 2007). With the advent of the new technologies of horizontal drilling and hydraulic fracturing, shale gas has increasingly become a main source of energy supply. Figure 1 shows the assessed shale gas basins in the world (USEIA, 2013; USGS, 2013). According to USEIA (2013), there is a total of 7,299 trillion cubic feet (tcf) of technically recoverable shale gas in the world, which is a 10.2% increase from prior estimates in 2011. This increase can be attributed to new shale gas basins discoveries. USEIA (2013) also listed the top ten countries with technically recoverable shale gas resources, including China (15.3%), Argentina (10.9%), Algeria (9.7%), the U.S. (9.1%), and Canada (7.8%). However, technically recoverable does not mean economically recoverable when considering the market and the current technology level of each country (Arthur et al., 2009; USEIA, 2013). For example, China has the greatest shale gas resource (Fig. 1), but it has not been developed much, mainly because of the technical challenges presented by fracking, water availability, and deficiency in infrastructure (Mauter et al., 2014; Wang et al., 2014).

In the U.S., shale gas occupied only 1.6% of natural gas production in 2000 but by 2010 increased dramatically to 23.1%, a 14-fold increase (Wang and Krupnick, 2013). The most active shale gas plays based on daily production include the Barnett Shale and the Marcellus Shale (Ground Water Protection Council and ALL Consulting, 2009; Kargbo et al., 2010; Table 1). The Barnett Shale play is located in the Fort Worth Basin of north-central Texas (Fig. 1), which is the oldest and was once the largest producing gas field in the U.S. (Martineau, 2007). Natural gas production with hydraulic fracturing started there in 1999, with 78.8 bcf (billion cubic feet) in 2000, and reached 2.09 tcf in 2012 (RRC, 2014), 26 times greater than in 2000. Meanwhile, Nicot and Scanlon (2012) reported that, in 2010, water used for fracking at the Barnett Shale comprised of about 9% of the 308 Mm^3 annual water use in Dallas, the 9th largest city in the U.S., and they foresaw there would be strong competition for water between the local water supply and the water-intensive shale gas enterprise.

The Marcellus Shale is located in the Appalachian Basin, across six states, including Pennsylvania and New York (Fig. 1), and now holds the largest store of recoverable shale gas in the U.S. (Yu and Sepehroori, 2014; Table 1). The Marcellus produced about 365 bcf of natural gas in 2007 and drastically increased its production to 5.1 tcf in 2014, about 18% of total natural gas production in the U.S. (USEIA, 2014). With the introduction of fracking, the Marcellus has been revitalizing since 2005 (Arthur et al., 2009). Considine et al. (2011) projected that, if the price of natural gas does not fall, gas production at the Marcellus could support 250,000 jobs, with state and local tax revenues of 2 billion dollars. Despite of economic benefits, there are concerns

Table 1. Statistics of Barnett and Marcellus shale plays in the U.S.

Parameters	Barnett Shale	Marcellus Shale
Main location	Texas	Pennsylvania (6 states)
Basin	Fort Worth Basin	Appalachian Basin
Age	Mississippian period (354–323 Ma)[a]	Devonian period (416–350 Ma)[d,f]
Coverage area	6,458 square miles[b]	94,893 square miles[b]
Depth	6,500–8,500 ft[a]	4,000–8,500 ft[c]
Thickness	300–500 ft[a]	50–200 ft[c]
Porosity	0.05–0.06[a]	0.08[c]
Total organic carbon	3.2 wt%[a]	12 wt%[b]
Gas in place	256 trillion cubic feet (tcf)[a]	1,500 tcf[c]
Technically recoverable gas	43.38 tcf[b]	141 tcf[c]; 410.34 tcf[b]; 489 tcf[f]
Average estimated ultimate recovery (EUR)	1.42 bcf/well[b]	1.18 bcf/well[b]
Reservoir temperature	150–180 °F (65–82 °C)[h]	120–150 °F (49–65 °C)[f]
First production with new technology	1999	2005[k]
No. of production wells	>2,340[a]; 8,294[g]; 15,856[b]; 14,900[j]	>7,109[i];

[a]Montgomery et al. (2005); [b]USEIA (2011); [c]Yu et al. (2014); [d]Soeder and Kappel (2009); [f]Kargbo et al. (2010); [g]Patzek et al. (2013); [h]Struchtemeyer et al. (2011); [i]Stateimpact (2014a), only for Pennsylvania; [j]Nicot and Scanlon (2012); [k]Harper (2008).

with development of the Marcellus Shale. The large amount of water used to stimulate the shale formation, about 3 million gallons per hydraulic fracturing operation, is of great concern to regional and local water managers in this area (Harper, 2008; Soeder and Kappel, 2009). Furthermore, environmental concerns regarding groundwater contamination due to fracking have still not been resolved (Beaver et al., 2014).

To date, the environmental externalities of shale gas development have not stopped most countries worldwide from pursuing the resource; the economic benefit and potential for energy security outweigh the costs. Thus, the continued development of shale gas implies the elevated potential for induced seismicity worldwide.

2.2. CO_2 Storage

A plausible method to tackle CO_2 emission is to capture the gas from fossil fuel-consuming facilities, including power plants and petrochemical companies, and store it underground (Martinsen et al., 2007; Park et al., 2014). Carbon capture and storage (or sequestration) (CCS) projects are widespread globally (Fig. 2; Kim, 2009; Global CCS Institute, 2014). However, CCS technology varies greatly by country, from basic research to field scale pilot injection, because of economic and political conditions as well as environmental perceptions (Haszeldine, 2009). Besides these hurdles, geological CO_2 sequestration requires some critical geological conditions, including tectonic stability and a large extent of rock formation with good porosity, appropriate depth, and a suitable cap rock (Gibson-Poole et al., 2006). Considering these factors, depleted oil and gas reservoirs, deep saline aquifers, and coal beds were first considered for geological sequestration (Metz et al., 2005; Michael et al., 2010; Park et al., 2014). In addition, reactive basaltic rocks have also been considered for injecting CO_2 to form carbonate minerals (Gislason and Oelkers, 2014). Sometimes, CO_2 injection can be combined with oil production to enhance oil and gas recovery in nearly depleted fields or unmineable coal beds (EPR, EGR, ECBM; Hill et al., 2013).

The U.S. is one of the countries researching innovative CCS technology and searching for appropriate sites for CO_2 injection. The U.S. government (USDOE) has formed a network of seven Regional Carbon Sequestration Partnerships to support technology development and to implement large scale CO_2 storage, including the Big Sky Carbon Sequestration Partnership, Southeast Regional Carbon Sequestration Partnership and West Coast Regional Carbon Sequestration Partnership, and it has also supported 23 small scale injection projects throughout the country (USDOE, 2012). The regional partnerships have focused on three phases including injection site characterization, small scale field injection, and large scale field injection (USDOE, 2012). The U.S. government is also collaborating with China, Germany, Norway and Algeria to disseminate its experience. As of October 2012, CO_2 injection was ongoing in the Illinois Basin

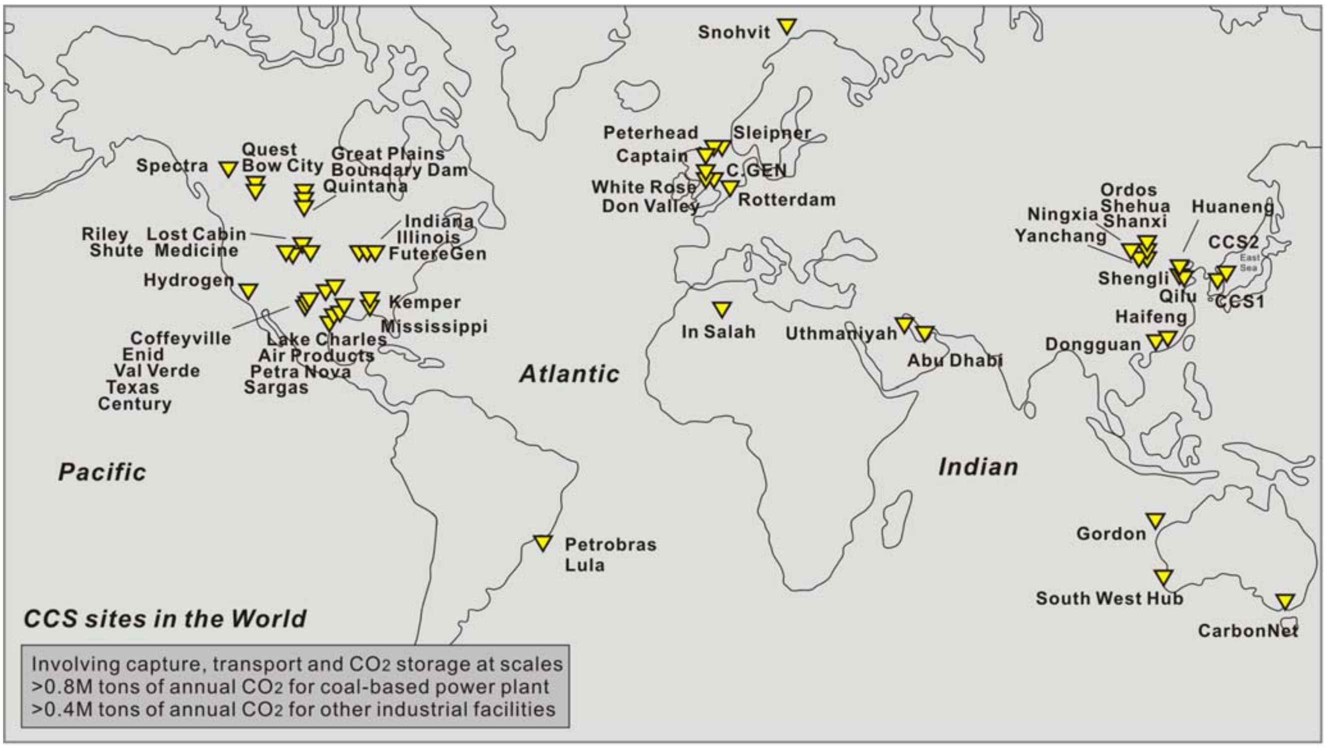

Fig. 2. Locations of large carbon capture and storage (CCS) sites in the world (as of 2014), involving capture, transport and CO_2 storage. The location data are from Global CCS Institute (2014). The site names are shortened for identification.

(sandstone reservoir) and the Gulf Coast (sandstone reservoir) with large target volumes of 1 to 3.4 million metric tons (USDOE, 2012).

China has long suffered from air pollution and is the top CO_2 emission country, mainly because of massive coal combustion (Seligsohn et al., 2010; Coneybeare, 2013). To tackle the greenhouse gas emission problem, China has prioritized the deployment of renewable energy rather than the CCS option (Coneybeare, 2013). With the implementation of necessary regulations, China announced the start of research on CCS technology in 2007, and is supporting leading energy companies to deploy CCS demonstration projects (Seligsohn et al., 2010; Best and Beck, 2011; Ming et al., 2014). As of 2013, China has 11 large-scale integrated CCS projects sequesting CO_2 volumes of 0.8 to 3 million tons per annum, including enhanced oil recovery (EOR) and geological storage (Coneybeare, 2013). China also has international cooperative CCS projects with the U.S., Australia, Canada, and the EU (GermanWatch, 2014).

Norway has been pursuing a variety of measures to develop CCS technologies, aiming to build a full-scale CCS plant by 2020 (Global CCS Institute, 2014). The country started one of the first CO_2 injection projects in the world and it has two fully operational offshore gas fields with CO_2 injection (Onarheim et al., 2015). Sleipner is an offshore gas field with CO_2 injection (800–1,000 m below sea floor) beginning in 1996 and Snøhvit is also an offshore gas field where CO_2 is injected at a rate of 700,000 ton per year below 2,560–2,670 m under the sea floor (Global CCS Institute, 2014). Most recently, Norway has agreed with the Czech Republic to cooperate in promoting CCS as an essential climate change mitigation technology (Bellona, 2015).

Australia is one of the leading countries for commercial CCS deployment with many demonstration projects, two flagship projects (South West Hub and CarbonNet), and developing interest in offshore CO_2 storage (CO2CRC, 2014). Canada commenced the world's first large-scale CCS project in the power sector in 2014 (Global CCS Institute, 2014). Based on the Canadian CO2 Capture & Storage Technology Roadmap (CETE, 2006), the country has been accelerating development of low greenhouse gas emission technologies. As of 2014, Canada has seven large-scale CCS projects and three of them are dedicated geological storage and four are related to enhanced oil recovery (Global CCS Institute, 2014). Japan is one of countries actively developing notable CCS projects even though it does not have large-scale projects (Global CCS Institute, 2014). Japan started four pilot and demonstration projects including the Tomakomai, COURSE 50, EAGLE and the Osaki CoolGen projects, from which it is intending to draw information on the development of large scale CCS projects and CO_2 behavior in the subsurface (Global CCS Institute, 2014).

Korea is one of the top 10 CO_2 emission countries in the world, and is also active in developing CCS technology (Jung et al., 2013). Most recently, the Korean government affirmed that CCS is one of the top six essential technologies to be developed in the near future, and thus the government will greatly elevate R&D funding to support it (investing 2.3 billion dollars by 2019; MEST, 2010). There are now two large R&D groups, the Korea Carbon Capture & Sequestration R&D Center (KCRC), funded by the Ministry of Science, ICT, and Future Planning since 2011, and the K-COSEM Research Center, funded by the Ministry of Environment since April 2014.

Complying with the Korea CCS 2020 plan (MEST, 2010), KCRC is focusing on third-generation technology development of CO_2 capture, innovative technology development integrating CO_2 capture and storage at the total capacity of 10,000 ton level, original technology development of CO_2 chemical and biological transformation and utilization, and establishment of CCS research infrastructure by 2020 (KCRC, 2014). K-COSEM is dedicated to developing technologies for environmental monitoring, risk assessment, and environmental management for CCS, and to modify relevant environmental laws and regulations for commercial deployment of CCS. Two CCS pilot projects are now ongoing (see Fig. 2), and are led by the Korean Electric Power Corporation, considering offshore CO_2 storage in the Ulleung Basin in the East Sea and the Kunsan Basin in the West Sea (Global CCS Institute, 2014; Kang et al., 2014; Zahid et al., 2014). In January 2015, a pilot injection of CO_2 on offshore Pohang was initiated (The Yeongnamilbo, 2015).

As seen above, the worldwide application of CCS, especially subsurface CO_2 injection, will continue to increase in the future. Future large-scale CCS projects pose the potential for induced seismicity worldwide, not limited to specific basins or regions.

3. INDUCED SESMICITY

3.1. Fracking and Wastewater Injection

Figure 3 shows a general schematic of fracking in shale gas development. The first step of fracking process is to inject a large quantity of water (2–4 million gallons per fracking) at high-pressure (20–50 MPa) to create a network of fractures in the formation which enhances reservoir permeability. The water is mixed with proppant such as sand and typically contains chemical additives (shown in inset in Fig. 3) (Perkins, 2014). The shattered rock, with the support of proppant, now contains permeable pathways to release trapped shale gas, mostly methane, which is pumped to the surface in a water/gas mixture.

During and after fracking, when the pressure is released, some of the injected fracking water is recovered (called flowback). During the production stage, some water is produced with the natural gas (called produced water) (Vidic et al., 2013), but it is not easy to distinguish between the two.

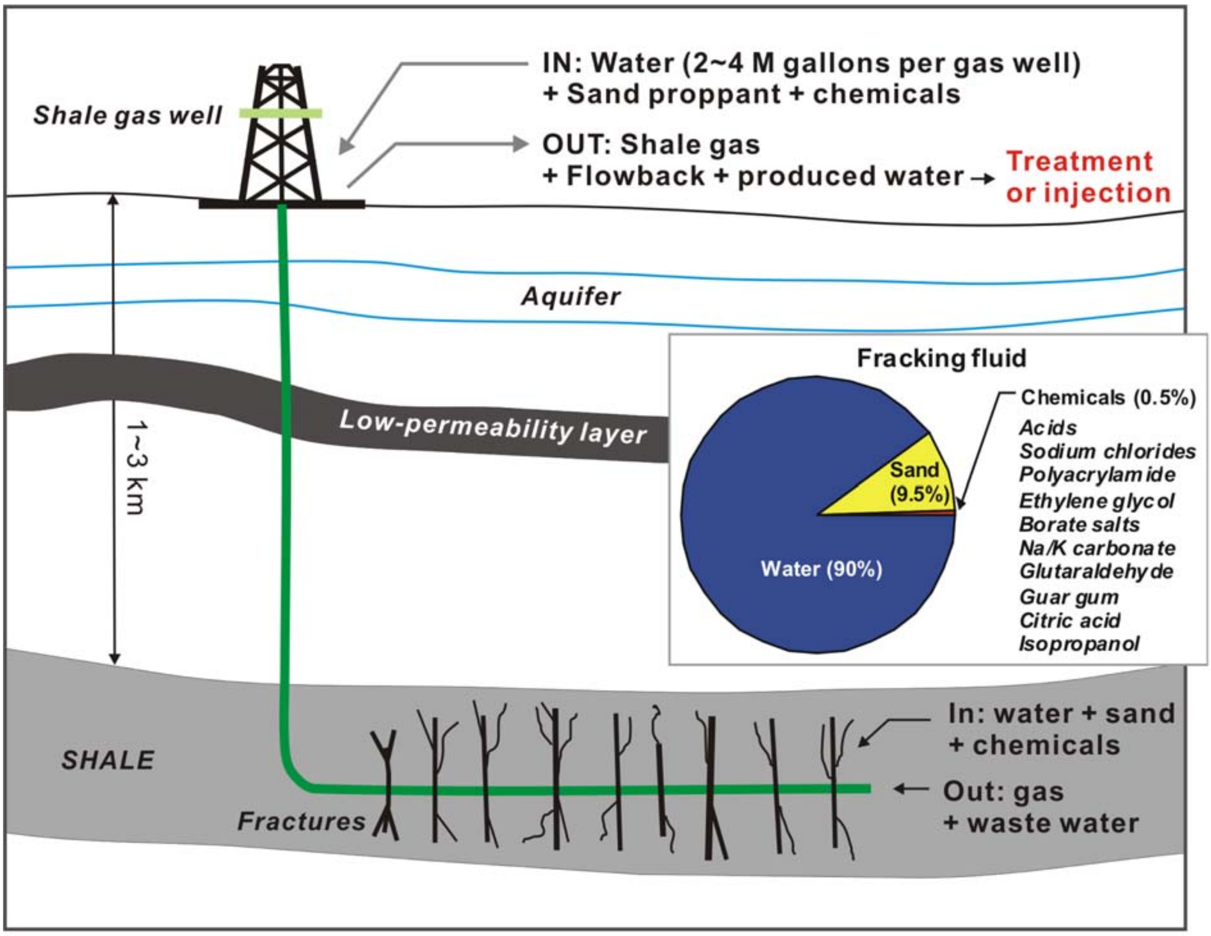

Fig. 3. Schematic of hydraulic fracturing (fracking) in shale gas development, also showing the components of the fracking fluid. The figure is modified from IEA (2011).

The flowback water, including the produced water, is generally considered to be 25% (range = 10–90%) of the total injected water (Haluszczak et al., 2013; Yang et al., 2013). Because the flowback contains proppant, chemicals, organics, high levels of salts, and natural radionuclides, it should be collected and treated prior to discharge (Kargbo et al., 2010; Haluszczak et al., 2013; Vengosh et al., 2013; Abualfaraj et al., 2014). However, this water is hard to treat, and the water treatment is expensive. In many cases, as an economical measure, the flowback or produced water is injected into nearby disposal wells (Kerr, 2012; Ellsworth, 2013; Vidic et al., 2013). However, the number of available, nearby disposal wells is limited, and it is costly to use remote disposal wells because of the need to transport the water. Meanwhile, shale gas production is expanding such that disposal wells are accommodating increasing volumes with very high injection rates, e.g., about 1.9 million m^3 per year per well (Keranen et al., 2014).

Subsurface fluid injection causes both a reservoir pore pressure increase and a perturbation to the stress field in the reservoir and surrounding rocks (NRC, 1990; Hsieh, 1996; NAS, 2013). Reservoir pore pressure increases promote slip along preexisting faults due to a reduction of the normal stress on the fault in the area where the pore pressure has been changed (Nicholson and Wesson, 1990; NAS, 2013). However, all fluid injection does not induce felt seismicity. It largely depends on geology and hydrogeology of the reservoir as well as the rate of fluid injection. Another crucial factor is the presence of faults optimally oriented to the regional stress field which are of sufficient size to produce felt earthquakes (NAS, 2013; McGarr et al., 2015).

The fracking (stimulation) water injection has been reported to induce seismicity (Smith, 2012; Ehrenberg, 2012; Davies et al., 2013; Ellisworth, 2013; NAS, 2013 and references therein). Ellisworth (2013) reported that the largest earthquake induced by the hydraulic fracturing process had a magnitude of 3.6, and thus did not pose a serious risk. Davies et al. (2013) compiled induced earthquakes worldwide that have occurred since 1929, from which they concluded that hydraulic fracturing operation itself cannot cause felt earthquakes. Ehrenberg (2012) suggested the more comprehensive conclusion that the largest earthquake in the U.S. related

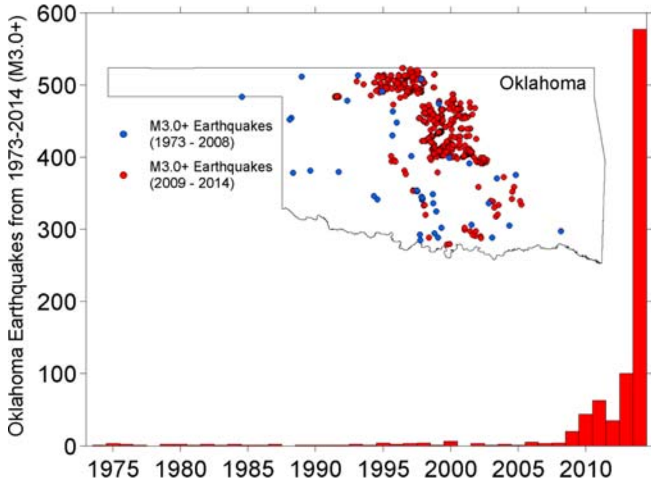

Fig. 4. Number of the earthquakes over magnitude 3 (*M*3.0+) occurred in Oklahoma from 1973 to 2014. The histogram and spatial distribution data are from USGS (2015).

to fracking had a magnitude of 2.8. Smith (2012) and McGarr (2014) also presented similar opinions, that the risk of induced seismicity associated with current fracking activity with proper management is low. Although it is not conclusive, many published papers and researchers have converged on the notion that fracking does not pose a large induced seismic hazard, but wastewater injection from fracking is risky with several *M*5.0+ earthquakes induced in the last 5 years.

Figure 4 shows the number of earthquakes of greater than *M*3.0 that have occurred in Oklahoma (see location in Fig. 1 and the inset map) since 1973 (USGS, 2015). Because the state of Oklahoma is tectonically stable, the average number of earthquakes recorded from 1973 to 1999 was only 1.6 per annum (USGS, 2014), but since 2009, earthquakes have drastically increased to nearly 600 in 2014 (USGS, 2015). The largest one, *M*5.6, hit Oklahoma in November 2011. This increase coincided with the start of wastewater injection in 2009. In this state, most of vertical gas production wells have evolved to horizontal wells since 2008, and from 2008, gas production and wastewater injection expanded dramatically (USDOE, 2009; Keranen et al., 2014). Keranen et al. (2013, 2014) attributed this unprecedented earthquake swarm to high-rate wastewater injection into disposal wells, drawing much attention from mass media and the public community, because swarms of quakes have continued in 2014 and several thousand disposal wells are active (as of 2013) in the state at depths of 3 to 6 km (Stateimpact, 2014b).

The risk of a potential *M*6.0+ earthquake in Oklahoma has doubled in the last 5 years. Earthquakes hazard across the central U.S. has also generally increased with case studies of injection-induced seismicity in the 2011 *M*5.3 Trinidad, Colorado earthquake (Rubinstein et al., 2014), the 2012 *M*4.8 Timpson, Texas earthquake (Frohlich et al., 2014), and the 2011 *M*4.7 Guy, Arkansas earthquake (Horton, 2012). Oklahoma, as well as other recent wastewater injection-induced seismicity, should serve as a cautionary tale to fracking and subsequent wastewater injection operations in new region and basins across the world.

3.2. CO_2 Injection

Figure 5 shows options for CO_2 injection into the subsurface (Metz et al., 2005). In addition to injection into deep saline aquifers, it can be used to recover residual oil and gas from the depleted oil and gas fields while also fulfilling the objective of CO_2 storage. The depth of CO_2 injection is rather shallower than shale gas production and wastewater injection, but the injection volume might be much larger (Mazzoldi, 2012). Induced earthquakes due to CO_2 injection have not been practically reported, because commercial deployment of geological storage has not begun (e.g., Miller et al., 2003; Lucier et al., 2006; Cappa and Rutqvist, 2011, 2012; Nicol et al., 2011; Mazzoldi, 2012; Zoback and Gorelick, 2012; Zakharova and Goldberg, 2014).

Based on a theoretical modeling study, Cappa and Rutqvist (2011) concluded that CO_2 injections can trigger earthquakes with a maximum magnitude of 4.5. Based on two earthquakes with magnitudes of 5.7 and 6.0 in Italy, Miller et al. (2003) suggested that the release of trapped high pressure CO_2 can trigger a large earthquake. Nicol et al. (2011) reported the similar result, from reviewing data from 75 sites in the world where water injection occurred, that commercial CO_2 injection (~50 Mt of total injection volume) can induce earthquakes of greater than *M*6, and their magnitudes would increase with injection size. However, Mazzoldi (2012) told a different story, suggesting that the maximum magnitude of earthquakes generated by CO_2 injection is in the range of *M*2.0 to *M*3.9. McGarr (2014) showed that the maximum magnitude of an induced seismic sequence is proportional to the total volume injected.

It has been noted that minor induced seismicity (*M*2–*M*3) can damage the seal integrity of the CO_2 reservoir even though the earthquakes are hardly felt on the surface, not resulting in human harm and building damage (Zoback and Gorelick, 2012). Even small to moderate earthquakes triggered by the injection or pressure changes in the repository can cause fractures in the upper low-permeability cap rock (Fig. 5) or reactivation of existing faults. Stored CO_2 may leak vertically through the fractures and reactivated faults (Chiaramonte et al., 2008).

We do not have seismic data from CO_2 injection at commercial scales, but this process is analogous to fracking water injection and wastewater injection with pressure. Considering the injection pressure, injection volume, and injection depth, we can reasonably infer that commercial CO_2 injection may induce felt earthquakes and their magnitudes could be larger than in the cases of fracking or wastewater injection.

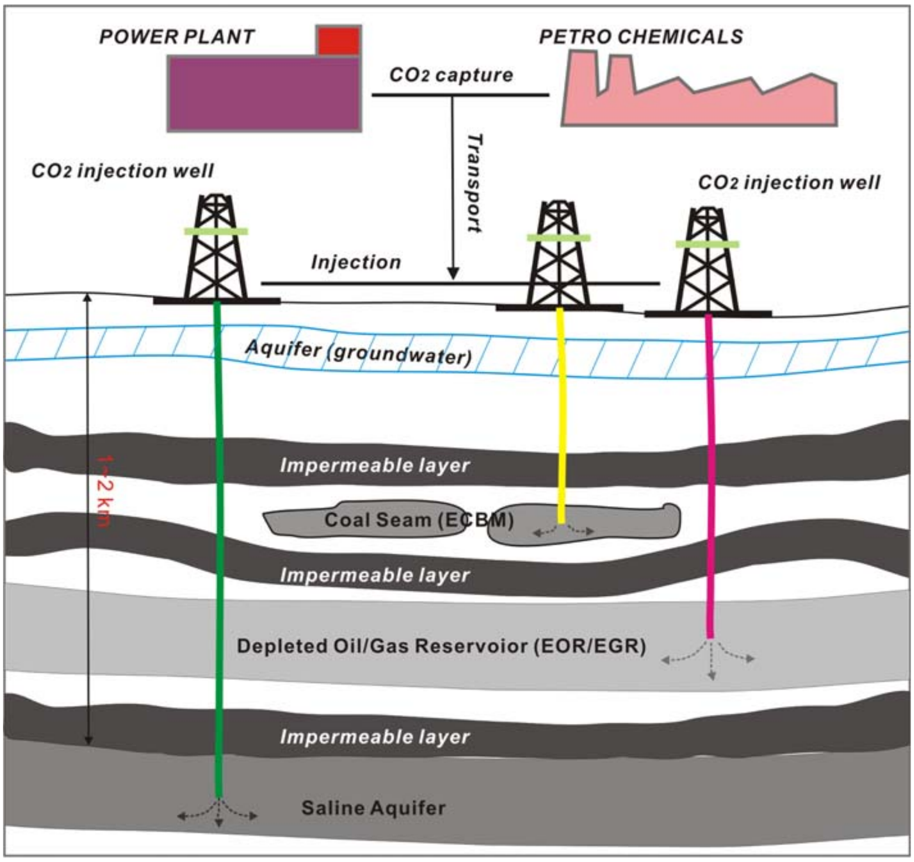

Fig. 5. Options of geological storage for carbon dioxide (CO_2). The figure concept and depth data are from Metz et al. (2005).

4. SUMMARY AND SUGGESTION

We have considered the current status of shale gas development and CO_2 geological storage, and reviewed their potential to induce earthquakes based on published literature and available internet resources. Although our review is not exhaustive, we reached following conclusions.

1) Unconventional shale gas production, with the help of horizontal drilling and hydraulic fracturing technologies, is greatly expanding globally. Fracking uses significant water resources, but the hydraulic fracturing process itself does not appear to induce large earthquakes. However, massive injection of wastewater into disposal wells causes earthquakes of greater than *M*5.0; without proper mitigation management, the earthquakes will continue in the near future.

2) As a way to avert the CO_2 emission problem, many countries are pursuing geologic storage of CO_2. Although commercial geological storage of CO_2 has not been implemented yet, the injection pressure, injection volume, depth, and the magnitude of induced earthquakes cannot be disregarded and even the minor seismicity can disrupt the seal integrity of CO_2 reservoir. Thus, planned commercial CO_2 geologic storage projects should attempt to quantify and mitigate the high potential for an induced earthquake.

Some economists and scientists (see Howarth et al., 2011) believe that the economic benefits of developing shale gas outweigh the disadvantages. However, for such development to be sustainable, injection should be optimized and managed to mitigate the hazard posed by significant induced seismicity. One mitigation strategy is to develop a seismic hazard model specifically tailored to the characteristics of induced seismicity in a particular region (McGarr et al., 2015). More importantly, prior to the onset of injection and subsequent felt earthquakes, detailed reviews need to be performed of a region's geologic and hydrogeologic structure with specific emphasis on the potential for induced seismicity.

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