Practical Reviews on CO_2 Sequestration in Korean Sedimentary Basins and Geophysical Responses of CO_2-injected Sediments

Le comportement pratiques sur la séquestration du CO_2 dans les bassins sédimentaires coréens et responses géophysiques de CO_2 injectées sédiments

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ABSTRACT: Geological CO_2 sequestration is an effective means of reducing the emission of carbon dioxide. The Korean government aims to reduce CO_2 emissions by 30% comparing to the usual amounts of emissions by 2020. It is expected that geological CO_2 storage technology will account for more than 10% of the reduction of CO_2 emissions. The forward strategies and technologies of CO_2 sequestration in Korea need to be determined depending on the geological conditions of potential sites in Korea; moreover, the geophysical characteristics of CO_2 and the reservoirs depend on the geological conditions. However, previous domestic studies related to geological conditions and the geophysical behavior of Korean sedimentary basins are rare thus far, with only a few studies focusing on numerical modeling. This study aims to review the geological characteristics of CO_2 storage projects around the world and in Korea while also discussing the suitability for CO_2 sequestration. Moreover, a laboratory approach simulating an in-situ high effective stress condition with silty sand from the Bukpyeong basin is attempted in an effort to determine the geophysical behaviors. This study offers an improved understanding of the possibility and potential of CO_2 sequestration in Korea.

RÉSUMÉ : La séquestration géologique du CO_2 est un moyen efficace de réduire les émissions de dioxyde de carbone. Le gouvernement coréen a pour objectif de réduire les émissions de CO_2 de 30 % à l'échéance de 2020. Il est prévu que la technologie géologique de stockage de CO_2 représentera plus de 10% de la réduction des émissions de CO_2. Les stratégies futures et les technologies de séquestration du CO_2 en Corée doivent être déterminées en fonction des conditions géologiques des sites potentiels en Corée, d'ailleurs, les caractéristiques géophysiques de CO_2 et les réservoirs dépendent des conditions géologiques. Toutefois, les précédentes études nationales relatives aux conditions géologiques et géophysiques sur le comportement des bassins sédimentaires de la Corée sont rares à ce jour, avec seulement quelques études mettant l'accent sur la modélisation numérique. Cette étude vise à examiner les caractéristiques géologiques des projets de stockage de CO_2 dans le monde et en Corée tout en discutant de leur pertinence pour la séquestration du CO_2. En outre, une approche de laboratoire simulant un état in situ à haute contrainte effective avec du sable limoneux du bassin Bukpyeong est tentée dans le but de déterminer les comportements géophysiques. Cette étude améliore la compréhension et la possibilité ainsi que le potentiel de séquestration du CO_2 en Corée.

KEYWORDS: CO_2 sequestration, korean marine sediment, geological condition, geophysical behavior

1 INTRODUCTION

Recently, several methods have been proposed to mitigate carbon dioxide (CO_2) emissions and to decrease the atmospheric concentration of CO_2, including material recycling, the usage of renewable energy, and nuclear fusion. Among these, *carbon capture and storage* (CCS) strategies are considered as effective methods of reducing the atmospheric concentration of CO_2 in a relatively short time at a low cost compared to other technologies (Espinoza et al. 2011; Pires et al. 2011). In light of this, approximately 40 CCS projects (including pilot-to-commercial scale applications) are in the planning or operational stages around the world (Hosa et al. 2010).

It has been reported that the increasing rate of CO_2 emissions in South Korea is the highest among OECD member countries, making Korea the seventh largest CO_2 emitting nation in the world (BP 2011). Since 1999, the atmospheric concentration of CO_2 in Korea has always been higher than the global average (Figure 1). The Korean government plans to reduce its CO_2 emissions by 30% compared to the current business as usual (BAU) value by 2020 (i.e., about 244 Mton/yr; Presidential Committee on Green Growth, 2011). It is prospected that geological CO_2 storage technology will account for more than 10% of global CO_2 emissions (approximately 25 Mton/yr). As a part of this effort, pilot (10000 tons of CO_2) and demonstration (100000 tons of CO_2) scale CO_2 sequestration projects, capable of storing more than 1 Mton of CO_2 in total, are currently planned and being conducted with commercial considerations in Korea (Presidential Committee on Green Growth 2011). This effort mostly relies on existing geologic data and resources that were gathered during oil explorations and drilling projects. However, the current geologic information on onshore and offshore deep subsurface areas of Korea is insufficient. Comprehensive geological exploration and database construction activities are critical for characterizing, selecting, or at least screening potential storage sites for CO_2 sequestration.

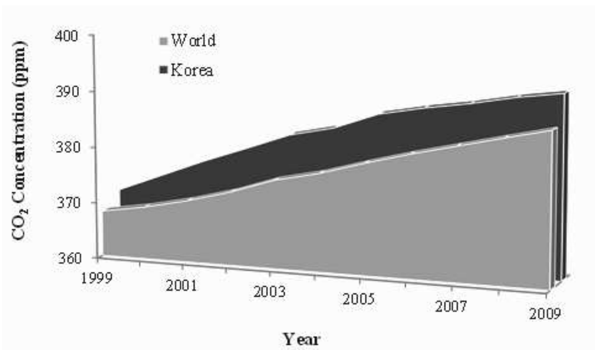

Figure 1. Atmospheric concentration of CO_2 of the world and in Korea. Data were gathered from Climate Change Information Center (www.climate.go.kr) and National Oceanic and Atmospheric Administration (www.noaa.gov).

Proper strategies and technologies for storing CO_2 in geologic formations must be determined with deep consideration of the geological conditions of the potential sites. Geological conditions (e.g., the pressure, geothermal gradient, geology, geochemical characteristics, and mineralogy) govern the interpretation of the geophysical responses of CO_2-storage reservoirs. Therefore, a fundamental understanding of the geophysical responses of CO_2-containing sediments in Korean sedimentary basins is required. However, while a few studies have been conducted on numerical reservoir modeling, there have been few efforts to examine the geological suitability for CO_2 storage and on geophysical characterizations of Korean sedimentary basins to date.

This study provides a review and discussion of the geological conditions and suitability of the potential CO_2 storage sites in Korea as well as CO_2 storage sites around the world. Moreover, laboratory experiment results on the P-wave velocity and the electrical responses of CO_2-injected sediments are presented, in which high *in-situ* effective stress conditions were simulated on natural samples cored from the eastern Bukpyeong basin, which is one of the candidate sites for geologic CO_2 storage.

2 SITE CHARACTERIZATION FOR CO_2 SEQUESTRATION

2.1 *Site-dependent strategies*

CO_2 can be stored in various geological formations, such as (1) deep saline formations, (2) coal beds, (3) depleted oil and gas fields, and (4) oil and gas reservoirs during enhanced oil and gas recovery efforts (EOR and EGR). Coal beds absorb and contain gaseous CO_2 in micro-pores in coal. However, the temperature and pressure effects on the CO_2 trapping process in coals are not well understood (Larsen, 2003). CO_2 storage in depleted oil and gas fields or the use of CO_2 for EOR (or EGR) have been proven as effective GCS methods due to the geological suitability for CO_2 storage, the existence of geophysical and geological data, and the ready-made infrastructure used for oil and gas production. However, several problems remain poorly identified, including well plugging, leakage induced by the overpressure of pore fluids, and the injection depth. Deep saline formation is the most promising method for safe and effective CO_2 storage due to its vast capacity. The potential storage capacity of deep saline formation is expected to be at least 1000 $GtCO_2$, which is approximately 200 to 300 times higher than the potential storage offered by oil or gas fields and coal seams (IPCC, 2005). In particular, sedimentary basins that have permeable formations (e.g., sandstone) with overlying low-permeable seals (caprocks) are effective for both CO_2 injection and CO_2 leakage prevention. The target depth is deeper than 1000 meters below the ground surface.

2.2 *Selected sites for CO_2 sequestration in America, Europe, and Asia*

There are more than 800 sedimentary basins around the world (St John et al., 1984). Approximately 40 CO_2 storage projects are under operation or in planning in North America, Europe, Australia, and Asia. Among them, ten onshore projects in the USA and two onshore projects in Canada are being conducted. Two onshore projects and three offshore projects in Europe are being undertaken, and two demo onshore projects in Japan are being tested (Hosa et al., 2010). Additionally, other potential sedimentary basins have been investigated and proposed for pilot-scale testing. For instance, the Alberta basin in Canada, where natural hydrocarbon resources had been found, was evaluated to be the most suitable basin in Canada owing to the existence of adjacent infrastructure (Bachu, 2003). The offshore Gippsland basin in Australia is considered as an effective target for CO_2 storage due to its complex stratigraphy, high injectivity, low-permeable marginal reservoir, the existence of several depleted oil fields, and its long migration pathways (Gibson-Poole et al., 2008). In China, an ECBM (enhanced coalbed methane recovery) pilot test and a single-well micro-pilot test were successfully performed at the South Qinshui basin (Wong et al., 2010).

One of the most well-known CO_2 storage attempts is the Sleipner project, targeting the Utsira Sand formation, which was launched in 1996. It was the first commercial-scale project to store CO_2 in a saline formation. The geologic condition of this site is a brine-saturated sandstone layer (250 m thick) with an overlying thin shale cap layer. Its storage capacity is expected to be 25 $MtCO_2$ (Hosa et al., 2010). The Nagaoka project at Nagaoka City, Japan, was the first pilot-scale attempt in Asia. In this pilot-scale test, CO_2 was injected into a Haizume-formation sandstone layer. The injection efficiency differs between the two formations (e.g., the Utsira Sand formation and the Haizume formation). In detail, the Utsira Sand formation (2800 tons/day) has a storage capacity of approximately 70 times that of the Haizume formation (a maximum 40 tons/day), as the permeability of the Haizume formation (i.e., 6 mD) is much lower than that of the Utsira Sand formation (i.e., 5 D) (Hosa et al., 2010) though both formations have relatively high porosities (37% for the Utsira formation and 22.5% for the Haizume formation) and similar injection depths (about 1000–1100 m). Therefore, it can be tentatively concluded that the permeability is a major controlling parameter for CO_2 injectivity rather than the porosity or injection depth.

2.3 *Geologic characteristics of sedimentary basins in Korea*

There are several potential geologic formations for GCS on the Korean Peninsula. The porosity, storage capacity, and geologic characteristics of those proposed sites are listed in Table 1. However, the geological information of offshore basins is still poorly identified due to insufficient exploration.

Table 1. Porosity and storage capacity of potential Korean geological storage sites

Basin	Porosity (%)	Storage Capacity (Mton)	Geologic Characterstics
Bukpyeong	N.A.	877[1]	Saline aquifer
Ulleung	10.6[2]	3,018[2]	EGR
Jeju	15.7[2]	95,101[2]	Saline aquifer
Gunsan	10[2]	254[2]	Saline aquifer
Heuksan	N.A.	N.A.	Saline aquifer
Pohang	N.A.	38[2]	Saline aquifer

[1]The values are from Kim et al. (2011) and [2]MEST (2008).

Korean offshore sedimentary basins have thickness ranges from 3 km to 10 km (MEST, 2008). The vast coverage area and high porosity of Korean offshore sedimentary basins are expected to show that these have larger storage capacities than onshore basins. Moreover, Korean offshore sedimentary basins show geologically structural similarity with natural hydrocarbon reservoirs, which indicates good suitability for GCS. For an example, the Gunsan basin and the Jeju basin show high potential for GCS because the geologic structures are similar to natural hydrocarbon reservoirs in analogous Chinese basins (Hong et al., 2005). The Ulleung basin contains natural gas deposits and is located more than 1000 m below the sea level. Thus, structural trapping may be feasible (Hong et al., 2005).

To evaluate the storage and economic efficiencies of sedimentary basins in Korea, a systematic and quantitative evaluation method (Bachu 2003) was employed in this study. Fifteen criteria (e.g., geological characteristics, basin resources, maturity, and infrastructure, among others) are considered with weight factors to assess the suitability (Table 2). Bachu's (2003) method classifies the proposed sites with dimensionless values between 0 and 1. The value can be used as a decision criterion for assessing the suitability of the proposed sedimentary basins for geological sequestration and for comparing it with basins in other countries in which pilot- and commercial-scale projects are already underway.

Table 2. Scores and weight assigned to the criteria and classes for assessing sedimentary basin in terms of their suitability for CO_2 sequestration in geological media (Bachu, 2003)

Criterion	Scores					Weight
	j=1	*j*=2	*j*=3	*j*=4	*j*=5	
Tectonic setting	1	3	7	15	15	0.07
Size	1	3	5	9		0.06
Depth	1	3	5			0.07
Geology	1	3	7			0.08
Hydrogeology	1	3	7			0.08
Geothermal	1	3	7			0.10
Hydrocarbon potential	1	3	7	13	21	0.06
Maturity	1	2	4		10	0.08
Coals and CBM	1	2	5			0.04
Salts	1	2	3			0.01
On/offshore	1	4	10			0.10
Climate	1	2	4	7	11	0.08
Accessibility	1	3	6	10		0.03
Infrastructure	1	3	7	10		0.05
CO_2 Sources	1	3	7	15		0.09

The evaluation results are summarized in Figure 2. Among other sites, the Ulleung basin was evaluated to be the most suitable site for geologic CO_2 storage in Korea due to the presence of nearby infrastructure as constructed for natural gas recovery.

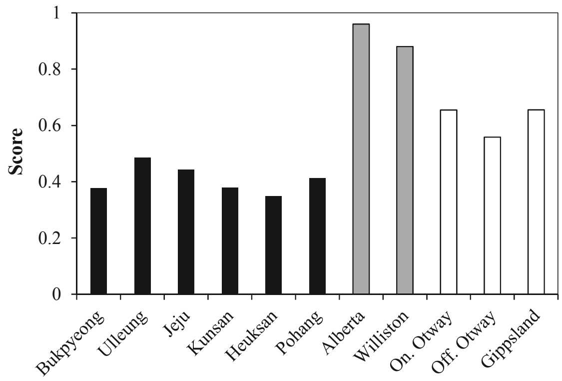

Figure 2. Scores for suitability for of Korean sedimentary basins.

However, the proposed sites in Korea are less feasible for geologic CO_2 storage compared to the basins in Canada and Australia. Specifically, the Korean basins show low scores on the following criteria: size, hydrocarbon potential, maturity, and infrastructure. Most Korean sedimentary basins, except the Ulleung basin, are estimated to be of a small-to-medium size, whereas the Otway and Gippsland basins in Australia are categorized as large and the Alberta and Williston basins in Canada are known to be large to giant in size. Moreover, a lack of boring studies and geophysical exploration exacerbate the problems of low maturity and insufficient infrastructure. Thus, more data acquisition and exploration are required to enhance the reliability of numerical modeling and simulations for the first Korean pilot project. Additionally, a new alternative approach involving the use of deep saline formations should be considered for safe and economic CO_2 sequestration in Korea with consideration of the geological characteristics of Korean basins and their limitations as regards CO_2 injection.

3 GEOPHYSICAL RESPONSES OF CO_2-CONTAINING SEDIMENTS

While CO_2 leakage from CO_2 stored sites could cause serious environmental problems, geophysical survey techniques are viable methods to detect CO_2 leakage and to identify CO_2 movement. Therefore, understanding the geophysical responses of Korean sediments during CO_2 injection and storage is important to ensure safety.

The most widely used geophysical methods are seismic surveys using P-waves and electrical resistivity surveys (Nakatsuka et al., 2010). In particular, feasibility of P-wave surveys for the detection of CO_2 has been examined in laboratory tests (Shi et al., 2007; Siggins et al., 2010; Xue and Lei, 2006). Also, it is well known that CO_2-containing formations have less stiffness than brine-saturated formations do (Daley et al., 2008; Lazaratos and Marion, 1997; Mito and Xue, 2011). Because the physical properties of unconsolidated sediments are significantly affected by the effective stress as well as the formation characteristics, achieving an in-situ effective stress condition is critical to obtain reliable physical properties of CO_2-containing sediments, though this may not be the case for cemented porous media. This section presents the geophysical responses of sediments in which an in-situ effective stress condition of the potential CO_2 storage sites was achieved.

3.1 *Experimental study*

The sediment sampled from the Bukpyeong basin (located on the east coast of Korea; see Table 1) was used in this study. The silty sand sample was compacted into a rigid-walled vessel and was saturated with water. Vertical in-situ effective stress of 15 MPa was then applied. The final porosity resulting from the applied stress condition was estimated to be 49%.

Table 3. Properties of test specimen

property	Soil type (USCS)	Specific gravity	Permeability (cm/s)	D50 (mm)
specimen	Silty sand	2.73	$4.2*10^{-5}$	0.15

The test was performed on saturated silty sand under a supercritical temperature condition (35°C) under the effective stress (15 MPa). The pore water pressure was maintained at 8 MPa using a back pressure regulator. The specimen was then flooded with supercritical CO_2. After a pre-determined amount of CO_2 was injected into a water-saturated sample, the geophysical responses (P-wave velocity V_P and electrical resistivity) were measured and the amount of injected CO_2 was estimated by measuring the amount of water expelled from the vessel.

3.2 *Results and analysis*

The total amount of water expelled by weight was 29.86 g; thus, approximately 30% of the pore water was displaced with supercritical CO_2, indicating that the CO_2 saturation rate was ~30%. The density and solubility of CO_2 at the target temperature and pressure are 591.85 kg/m^3 (NIST) and 1.35 mol/kg of water (Duan and Sun 2003), respectively. Accordingly, the total calculated amount of injected CO_2 was 17.29 g.

Figure 3 shows the decrease in V_P during the CO_2 injection process. The decrement range is relatively low compared to pre-existing studies (Shi et al. 2007; Siggins et al. 2010). This can be explained by the fact that the CO_2 injectivity in sandy soil specimens is lower than that in sandstone. The electrical resistivity increased rapidly as CO_2 was introduced. The convergence of the electrical resistivity indicates a fully saturated condition in which no more CO_2 can be injected (see Figure 4). The overall results show that CO_2 can be detected by measuring the geophysical properties; however, the injected amounts and readings of the movement of CO_2 are not highly precise.

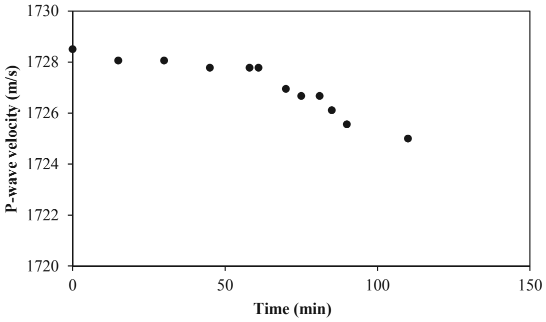

Figure 3. The effect on the P-wave velocity of the sediment during CO_2 injection.

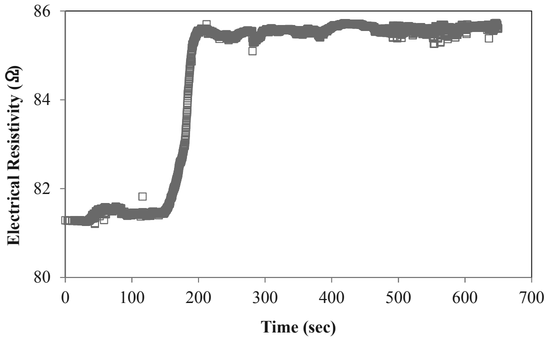

Figure 4. The electrical resistivity of the sediment during CO_2 injection.

4 CONCLUSION

The presented study explores practical reviews on Korean marine sediments for CO_2 sequestration in relation to geological and geotechnical considerations. The geological conditions of off-shore sedimentary basins in Korea were investigated, and the suitability of the basins for CO_2 storage were evaluated. The Ulleung basin were found to be the most suitable site for GCS, although their scores were lower than the scores of some basins where CO_2 storage is currently undergoing or pilot-tested in Canada and Australia. Geophysical behavior of CO_2-storing sediments is available for field application to monitor CO_2 movements and leakages. A laboratory scale experiment simulating the in-situ condition for measuring geophysical properties, and the results showed that CO_2 can be detected by measuring geophysical properties but further study is required to exact understanding geophysical behavior of CO_2-storing Korean marine sediments.

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