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# Carbon Dioxide Geological Storage: Monitoring Technologies Review

Guoxiang Liu
*Department of Civil and Environmental Engineering West Virginia University*
*USA*

## 1. Introduction

With anthropogenic activities, the concentration of $CO_2$, one of the greenhouse gases along with $CH_4$, $NO_2$, NO etc., is increasing in the atmosphere. As shown in Davison et al. (2004), the most abundant greenhouse gas, $CO_2$, has risen from a preindustrial level of 270 parts per million by volume (ppmv) to over 380 ppmv (Keeling & Whorf, 1998; Metz, Davidson, Coninck, Loos & Meyer, 2005) with an accumulation rate of about 1.5 ppmv per year (Halmann & Steinberg, 1999; Hansen et al., 1997). At the current increasing rate, $CO_2$ concentration in the atmosphere could be more than 700 ppmv by the end of this century (Halmann & Steinberg, 1999; Hansen et al., 1997; Metz, Davidson, Coninck, Loos & Meyer, 2005; Metz, Davidson, de Coninck, Loos & Meyer, 2005) due to around 6 Gt $CO_2$ emissions globally from fossil-fuel combustion used for generating electricity, transportation and some industrial processes etc. each year (Metz, Davidson, de Coninck, Loos & Meyer, 2005). The enormous $CO_2$ amounts injected into the environment have resulted in a series of global problems, such as warming of the Earth's surface, increasing extreme weather, polar ice melting, and desert size increasing. For example, the global average surface temperature of the Earth has increased by approximately $0.74 \pm 0.18\,^{\circ}C$ over 1906-2005 (Trenberth & Jones, 2007). The Intergovernmental Panel on Climate Change (IPCC) has predicted an average global rise in temperature of about 1.4 to 5.8 °C between 1990 and 2100 (Metz, Davidson, Coninck, Loos & Meyer, 2005). Although the cause and effect relation between the atmospheric concentration of $CO_2$ and global warming is still uncertain, the increase in emissions of $CO_2$ and other greenhouse gas has caused public concern worldwide (EPA, 2005; Metz, Davidson, de Coninck, Loos & Meyer, 2005).

However, the concentration of $CO_2$ in the atmosphere can be reduced by capturing and disposing of the produced $CO_2$ in geological formations for a long time (Herzog & Drake, 1996; Metz, Davidson, de Coninck, Loos & Meyer, 2005; Reichle et al., 1999). This is called carbon capture and sequestration (CCS). CCS may bring other benefits, such as coal-bed methane recovery, enhanced oil recovery, enhanced gas recovery, or even water production. At present, there are several options of $CO_2$ sequestration being discussed. One is to inject the $CO_2$ into deep coalbeds, where it will be adsorbed by the coal, typically replacing methane that can be recovered. Another option is to pump the $CO_2$ into saline formations where the $CO_2$ dissolves into the ambient fluid (Bergman & Winter, 1995; Gunter et al., 1996; Metz, Davidson, de Coninck, Loos & Meyer, 2005). Storing the $CO_2$ in depleted oil or natural gas reservoirs where it replaces the residual oil or gas is another option (Davison et al., 2004).

Moreover, the $CO_2$ can be sequestered in oceans and ecosystems (Lorenz & Lal, 2010; Metz, Davidson, Coninck, Loos & Meyer, 2005; Metz, Davidson, de Coninck, Loos & Meyer, 2005; Voormeij & Simandl, 2002). The potential capacity of $CO_2$ storage in these sites is estimated as 20,000 billion tons (Herzog & Golomb, 2004).

Once $CO_2$ is injected into a geological formation, it can be trapped in the pore spaces by four main processes. The first process is stratigraphic and structural trapping. This means that the $CO_2$ is trapped in the pore space by overlying low permeability rock-cap (caprock) seal(s). This trapping depends on the strata and structure of the geological formation. Another process is residual gas trapping, which means that the $CO_2$ is sequestered in the matrix of media. Capillary pressure is the main factor providing the stability of this trapping. Solubility trapping refers to $CO_2$ dissolving into the fluid of the geological formations, such as water. Finally, $CO_2$ can react with solid materials and become mineralized. Since the mineralization process depends on factors like pH and chemical species, it takes longer than other mechanisms, but of the four processes, this trapping is more stable over time (Bachu et al., 1994; Gunter et al., 1993). However, whatever the mechanism of $CO_2$ sequestration in different media such as saline basins or coal reservoirs, the basic idea for the geological sequestration is to find suitable geological structures that have sufficient pore space to hold the $CO_2$, and an impermeable cap-rock to seal $CO_2$ within the storage reservoir without long-term leakage (Metz, Davidson, de Coninck, Loos & Meyer, 2005).

As the literature reports, there are several modes of $CO_2$ leakage back to the atmosphere. For example, injected $CO_2$ can leak out along fractures and faults, especially with large pressure gradients and high injection rates (Metz, Davidson, de Coninck, Loos & Meyer, 2005). If the effective stress of the reservoir rises to its maximum limitation due to $CO_2$ injection, there is a large potential risk of structural deformation and fracture, resulting in $CO_2$ leakage from the reservoir. Ultimately, this means $CO_2$ sequestration failure of the site (Lee et al., 2005; Liu & Smirnov, 2008; 2009; Pekot & Reeves, 2003). Injected $CO_2$ may escape through poorly plugged and/or old abandoned wells, even due to corrosion within the well, plugging cement and surrounding material. Moreover, ground water can bring dissolved $CO_2$ out of a geological formation. Figure. 1 shows these potential leakage mechanisms from geological sequestration, as well as related remedial methods (Metz, Davidson, de Coninck, Loos & Meyer, 2005). In addtion, there are also some meteorological factors, such as atmospheric pressure variations, wind near the ground surface, temperature variation, and rainfall (Chen & Nash, 1994; Guo et al., 2008; Liu, 2010; Neeper, 2001; Oldenburg, Lewicki & Hepple, 2003; Oldenburg, Unger, Hepple & Jordan, 2003; SEAI, 1996; Sturman, 1992; Taylor, 1970) that have effects on the $CO_2$ leakage, especially in the near-surface of vadose zone. These potential leakages of injected $CO_2$ mainly result from the reasons below (NETL, 2011).

- Undetected faults, fracture and/or potential fast flow paths.
- Fracture or fault change caused by stress or geochemical reactions.
- Confining penetration by geochemical reactions.
- Unintended lateral flow.
- Wellbore failure events.
- Natural disasters such as earthquake etc.

These will require deep and shallow monitoring by geophysical techniques, well related facilities, and modeling simulations to confirm the behaviors of $CO_2$ which cover:

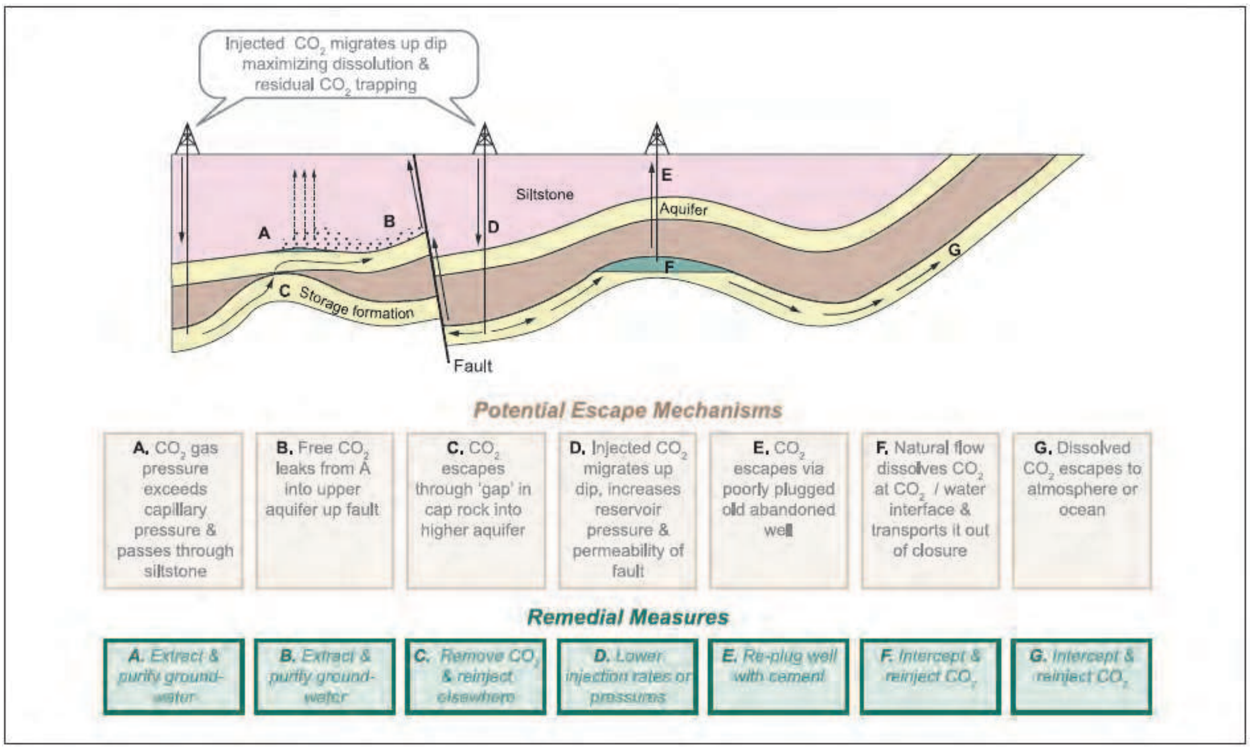


Fig. 1. Potential $CO_2$ escape mechanisms from geological formations and remediation techniques (Metz, Davidson, de Coninck, Loos & Meyer, 2005).

- $CO_2$ movement in the storage reservoir over time.
- Pressure changes in and around the storage reservoir due to $CO_2$ injection.
- $CO_2$ migration from primary storage reservoir.
- $CO_2$ migration in shallow depths through overburden.
- $CO_2$ detection/measurement near/at the surface.

Moreover, $CO_2$ leakage may happen not right above of the storage site but kilometers away, which strongly depends on the local geological structure. The upward migration dipping the high permeable formation such as sandstone and thus appear the leakage several kilometers away from storage site. Depending the leakage path and permeability, the leakage may occur after hundreds of years but it still highly significant. All of statements above require a $CO_2$ monitoring system which combine with the processes of site characterization, modeling prediction, risk assessment, and remediation and regulation.

For sake of monitoring and predicting $CO_2$ leakages stated above, there are more and more methods that have been developed in recently years (Abu-Khader, 2006; Dasgupta, 2006; Gale, 2004; Liu, 2010; Liu & Smirnov, 2009; Smith, 2004; Sweatman & McColpin, 2009). The potential leakage can be surveyed by monitoring variation values of the formation pressure, stress, $CO_2$ plume, $CO_2$ density, and chemical component by numerical simulations, seismic methods, gravimetric strategies, and electromagnetic technologies. The monitoring also focuses on the near-surface and surface monitoring by flux measurement tools, remote sensing equipments, acoustic image and sonar methods, and numerical simulations.

In this chapter, all of the above mentioned methods, strategies, technologies, and tools for $CO_2$ monitoring will be reviewed in details. Their applications to $CO_2$ storage in fields will be presented based on the recently projects and practices in worldwide such as Sleipner in the North Sea, Salah in Algeria, Weyburn in Canada, Gorgon in Australia, seven Regional Carbon Sequestration Partnerships in United States etc. Inducting suggestions would be discussed through the reviewing of monitoring technologies based on the comparisons of these field applications.

## 2. Review of monitoring technologies

The main purpose of monitoring $CO_2$ is to confirm the storage of the $CO_2$ without significant leakage for a long-term period to meet the regulation and environmental policy. In view of the monitoring, there are various methods such as geophysics based, geochemistry based, well based etc. that rely on the specific storage location and monitoring objective as follows (IEA, 2007):

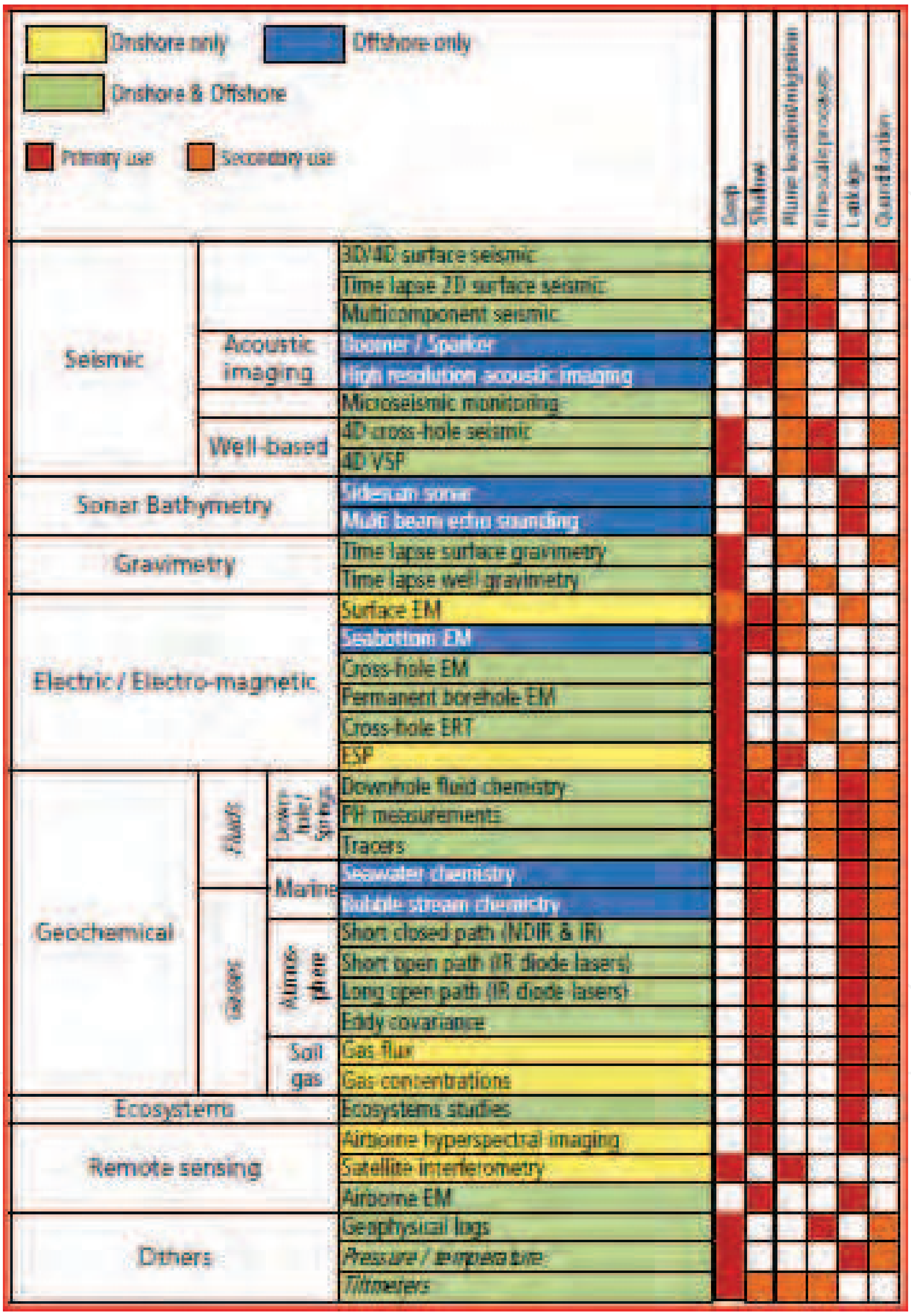
- Reservoir location: on-shore or off-shore
- Reservoir type: brine, oil, gas, or coal-bed
- Reservoir depth
- Quantity of injected $CO_2$
- Land use at proposed storage site: populated, agricultural, wooded, arid, or protected
- Monitoring phase: pre-injection, injection, post-injection, post-closure
- Monitoring objective: plume, top-seal, migration, quantification, efficiency, calibration, leakages, seismicity, integrity, or confidence

Moveover, the monitoring can be focused on the deep and/or shallow formation(s) even though the surface leakage flux or the atmospheric concentration of $CO_2$. The purpose of the deep monitoring is to track the movement of $CO_2$ within the storage reservoir and its migration into surrounding formations. This can help to confirm how much $CO_2$ is stored in the target reservoir. It further helps to adjust and optimize the storage and injection options. Another main objective of the deep monitoring is to track the passway of $CO_2$ migration from deep to shallow to avoid leaking. Deep monitoring system can be implemented by the surface-based techniques such as surface seismic and/or deep-based methods like monitoring well. The main purpose of the shallow monitoring is to detect $CO_2$ that has migrated into shallow overburden or surface/atmoshpere. So, most of the techniques based on the gas and flux detection can be used for this monitoring purpose.

The potential monitoring technologies are listed in Figure 2 ($CO_2$STORE, 2007). However, many of them have not been tested on the real sites of $CO_2$ storage. These technologies can be grouped based on the monitoring purpose such as deep and shallow, plume tracking, fine-scale processes etc ($CO_2$STORE, 2007). In this section, most of the monitoring technologies that have been used in the $CO_2$ storage fields will be reviewed.

### 2.1 Seismic technologies

The seismic technology was started in the 1930s for the 2D geological data acquirement. However, the real ability to acquire and process 2D seismic data was developed in the 1950s (Davies et al., 2004). With the acquisition of multiple closely spaced lines such as 25 m with 2D seismic image, the data can provide the 3D migration during processing. These lead to a volume from which lines, planes, and slices in any orientation for three dimensions, which are 3D seismic data (Lonergan & White, 1999). The 3D close line spacing has a potential to



🟨 Onshore only 🟦 Offshore only

🟩 Onshore & Offshore

🟥 Primary use 🟧 Secondary use

| | | | | Deep | Shallow | Plume location/migration | Fine-scale processes | Leakage | Quantification |
|---|---|---|---|---|---|---|---|---|---|
| Seismic | | | 🟩 3D/4D surface seismic | 🟥 | 🟧 | 🟥 | 🟧 | 🟧 | 🟥 |
| | | | 🟩 Time lapse 2D surface seismic | 🟥 | | 🟥 | 🟧 | | |
| | | | 🟩 Multicomponent seismic | 🟥 | | 🟥 | 🟥 | | |
| | Acoustic imaging | | 🟦 Boomer / Sparker | | 🟥 | 🟧 | | 🟥 | |
| | | | 🟦 High resolution acoustic imaging | | 🟥 | 🟧 | | 🟥 | |
| | | | 🟩 Microseismic monitoring | | | 🟧 | | | |
| | Well-based | | 🟩 4D cross-hole seismic | 🟥 | | 🟧 | 🟥 | | 🟧 |
| | | | 🟩 4D VSP | 🟥 | | 🟧 | 🟥 | | |
| Sonar Bathymetry | | | 🟦 Sidescan sonar | | 🟥 | | | 🟥 | |
| | | | 🟦 Multi beam echo sounding | | 🟥 | | | 🟥 | |
| Gravimetry | | | 🟩 Time lapse surface gravimetry | 🟥 | | 🟧 | | | 🟧 |
| | | | 🟩 Time lapse well gravimetry | 🟥 | | | 🟧 | | |
| Electric / Electro-magnetic | | | 🟨 Surface EM | 🟧 | 🟥 | 🟧 | | 🟧 | |
| | | | 🟦 Seabottom EM | 🟥 | 🟥 | 🟧 | | | |
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| Geochemical | Fluids | Down-hole / Springs | 🟩 Downhole fluid chemistry | 🟥 | 🟥 | | 🟧 | 🟥 | 🟧 |
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| | | Marine | 🟦 Seawater chemistry | | 🟥 | | | 🟥 | 🟧 |
| | | | 🟦 Bubble stream chemistry | | 🟥 | | | 🟥 | 🟧 |
| | Gases | Atmos-phere | 🟩 Short closed path (NDIR & IR) | | 🟥 | | | 🟥 | 🟧 |
| | | | 🟩 Short open path (IR diode lasers) | | 🟥 | | | 🟥 | 🟧 |
| | | | 🟩 Long open path (IR diode lasers) | | 🟥 | | | 🟥 | 🟧 |
| | | | 🟩 Eddy covariance | | 🟥 | | | 🟥 | 🟧 |
| | | Soil gas | 🟨 Gas flux | | 🟥 | | | 🟥 | 🟧 |
| | | | 🟨 Gas concentrations | | 🟥 | | | 🟥 | 🟧 |
| Ecosystems | | | 🟩 Ecosystems studies | | 🟥 | | | 🟥 | |
| Remote sensing | | | 🟨 Airborne hyperspectral imaging | | 🟥 | | | 🟥 | 🟧 |
| | | | 🟨 Satellite interferometry | 🟥 | | 🟥 | | | |
| | | | 🟩 Airborne EM | | 🟥 | | | 🟥 | |
| Others | | | 🟩 Geophysical logs | 🟥 | | | 🟥 | | 🟧 |
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Fig. 2. Potential $CO_2$ monitoring methods and tools ($CO_2$STORE, 2007).

produce stratigraphic resolution, imaging of structural and depositional dips, and migration by the automatic or semi-automatic tracking of density of the surface reflection. It means that the characteristics such as fault systems can be mapped in much more detail than one only with 2D seismic data (Freeman et al., 1990).

With development of the seismic technology, the interpretation of seismic data become more accurate and powerful to reflect geoscience, such as identification of stratigraphy, structural geology, igneous geology. Some new techniques, such as 4D seismic and 4C seismic have been applied to investigate the characteristic changes over time to strength the static image from 3D data by introducing time lapse and longitudinal (P-) waves and transverse (S-) waves (Davies et al., 2004). These techniques can be used both at the surface and downhole. The following sections will provide more details of the seismic technologies.

### 2.1.1 4D seismic technologies

4D seismic is a time-lapse seismic survey, which involves acquisition, processing, and interpretation of the repeated seismic surveys (3D seismic) with time intervals for field site. The major applications of the seismic technologies in monitoring include two types of reservoir property identification due to spatial sensitivity of seismic images. The first one is the static geology properties such as porosity, lithology, shale content. The second one is the dynamic properties based on the fluid flow, such as pressure, temperature, fluid saturation (Lumley & Behrens, 1998). As well known, the operation of seismic survey is to generate the seismic sources, such as dynamite, airguns, vibrators at/near earth surface, and then record the reflected seismic waves from subsurface by receivers (hydrophones or geophones) at/near surface, using a wave-equation-imaging algorithm to create seismic image of the fluids and reservoir properties by contrasting the reflections (Claerbout, 1985).

The time-lapse signal is affected by compressibility of the reservoir rock and the pore fluids because acoustic impedance is the production of velocity and density. So, if the fluids with big difference of density such as gas-water,gas-oil, light oil, the monitoring is much easier than the one with small difference of density such as heavy oils (Lumley, 2001). The basic relationships among porosity, rock property, and fluid property for 4D seismic monitoring were suggested by Lumley and Behrens (Lumley & Behrens, 1998). As shown in Figure 3, the top one indicates how the seismic impedance varying with the change of porosity for oil-full to water-swept conditions; the bottom one shows that compressible and high porosity geological formations are better options than the other rigid, low porosity ones for 4D seismic monitoring (Lumley & Behrens, 1998).

Before a seismic survey is performed, usually, four steps were suggested to be followed for the feasibility and risk assessment on whether 4D seismic is able to image the desired reservoir and fluid properties (Lumley & Behrens, 1998).

- Evaluating the primary critical variables of the seismic technique and reservoir for the success of 4D seismic survey. Mostly, there are three questions to help to figure out the criteria. What is the compressibility range (high, medium, and/or low) of the reservoir rock? Is there sufficient fluid saturation changes to be surveyed over time? Is there a highly probability to obtain high quality 3D seismic data in the study area (Lumley & Behrens, 1998; Lumley et al., 1997)?

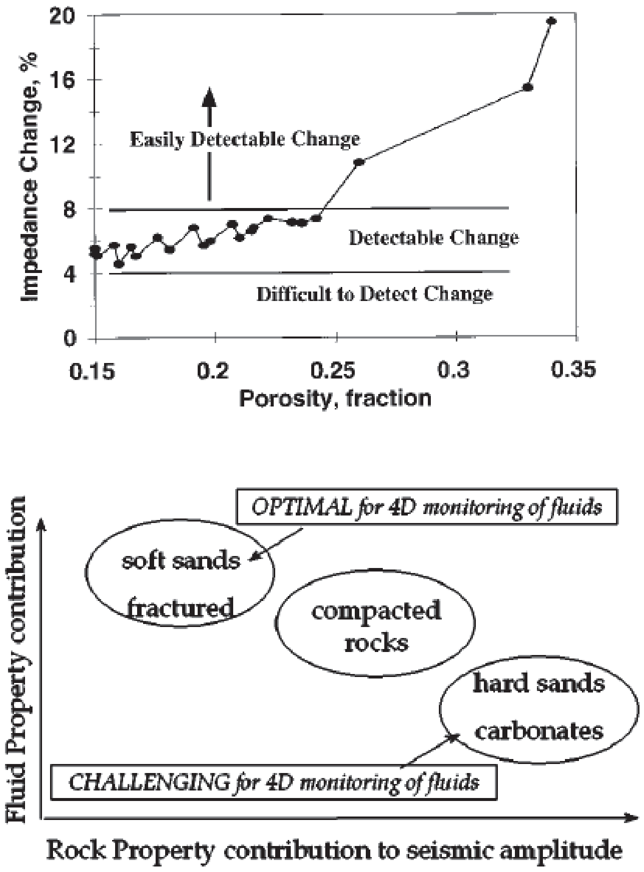


Fig. 3. The basic relationships among porosity, rock property and fluid property for 4D seismic monitoring (Lumley & Behrens, 1998). The bigger porosity media is easier to be detected by 4D seismic survey as shown in the top of the figure. The bottom of the figure indicates that the more soft media is more suitable for 4D seismic to monitor the fluids.

- Determining the properties (static geological characteristics and dynamic fluid-related properties) of specific reservoir rocks in reservoir conditions by core measurements with reference of Figure 3 (Lumley & Behrens, 1998; Wang, 1997) .

- Pre-testing the range of properties of the study area, seismic frequency content, full waveform effects, reflection angle and amplitude effects by modeling seismic traces from core data and well logs to calibrate seismic data at possible well locations (Lumley & Behrens, 1998).

- Computing time-lapse 3D synthetic seismic images by using detailed reservoir and flow simulations (Lumley & Behrens, 1998).

Beyond above four steps for helping decision-making in the procedure of 4D seismic survey, the risk of 4D seismic may reduce during the acquire in the field investigation if with consideration of the new proposed workflow as shown in Figure 4 (Lumley & Behrens, 1998). This workflow integrates the 4D seismic survey (with seismic history matching) in the reservoir modeling procedure to improve the reservoir characteristics. This means that the monitoring methods based on the modeling (simulation) correspondingly are improved.

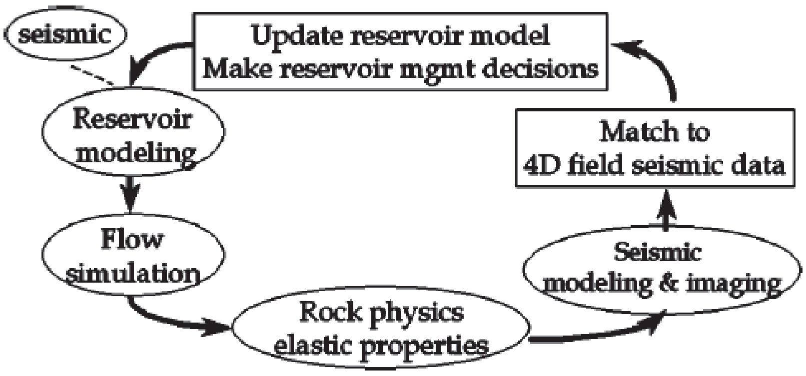


Fig. 4. A workflow proposed for reservoir applications of 4D seismic technologies (Lumley & Behrens, 1998).

In $CO_2$ monitoring, the purpose of seismic technique is to determine the changes in seismic properties (mostly acoustic impedance) that resulted from $CO_2$ injection by comparing the surveys among time-lapse seismic data set. An example in Figure 5 shows the results of $CO_2$ plume during injection from a 4D seismic simulation study in a West Texas carbonate reservoir (Lumley & Behrens, 1998).

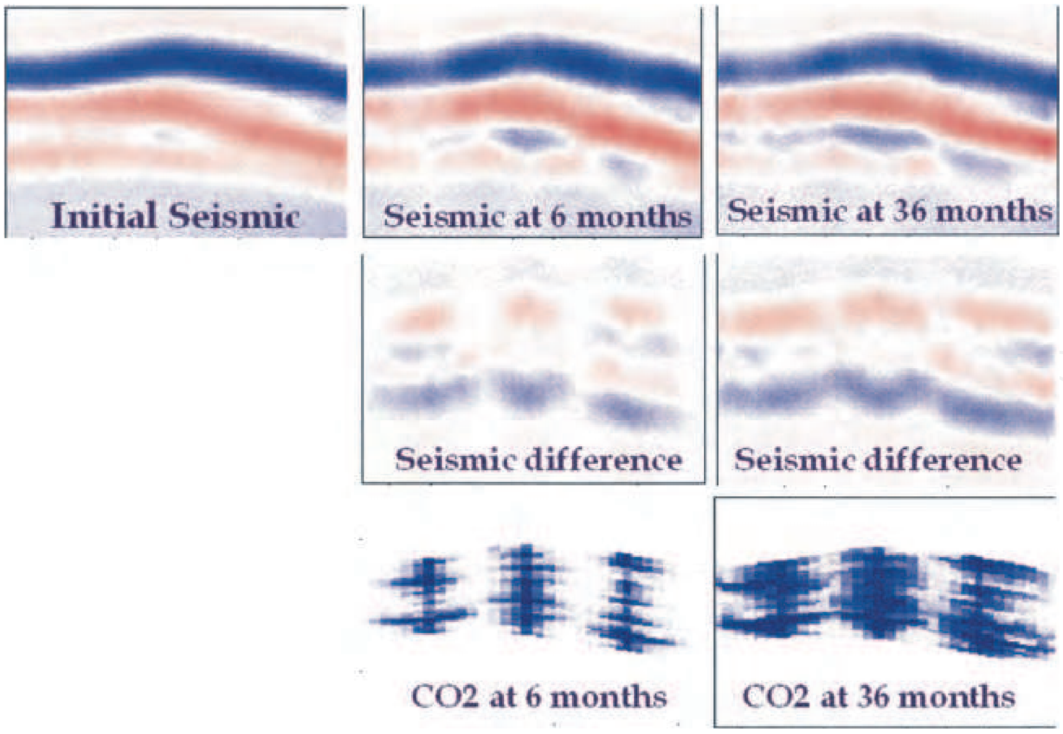


Fig. 5. An example of $CO_2$ migration using time-lapse seismic techniques for six and 36 months monitoring (Lumley & Behrens, 1998).

### 2.1.2 Other seismic techniques

**Micro-Seismic Technique**: Micro-seismic also called passive seismic or minute tremors which is an option to monitor pore pressure and geomechanical stress variations due to $CO_2$ injection. One of the wide applications is to characterize the zones of weakness (such as overburden) in the storage site and tracking the flow pathways for $CO_2$ movement (including movement of contaminants due to $CO_2$ injection) and/or leakage monitoring (Dasgupta, 2006; DTI, 2005). This includes caprock/seal integrity and pre-existing fault or fracture networks identification. An example for fluid pathway tracking by micro-seismic is provided in Figure 6 (Dasgupta, 2006). Moreover, micro-seismic demonstrated the possibility on geomechanical behavior such as deformation monitoring by acquiring real-time events of the seismic survey (Verdon, 2010).

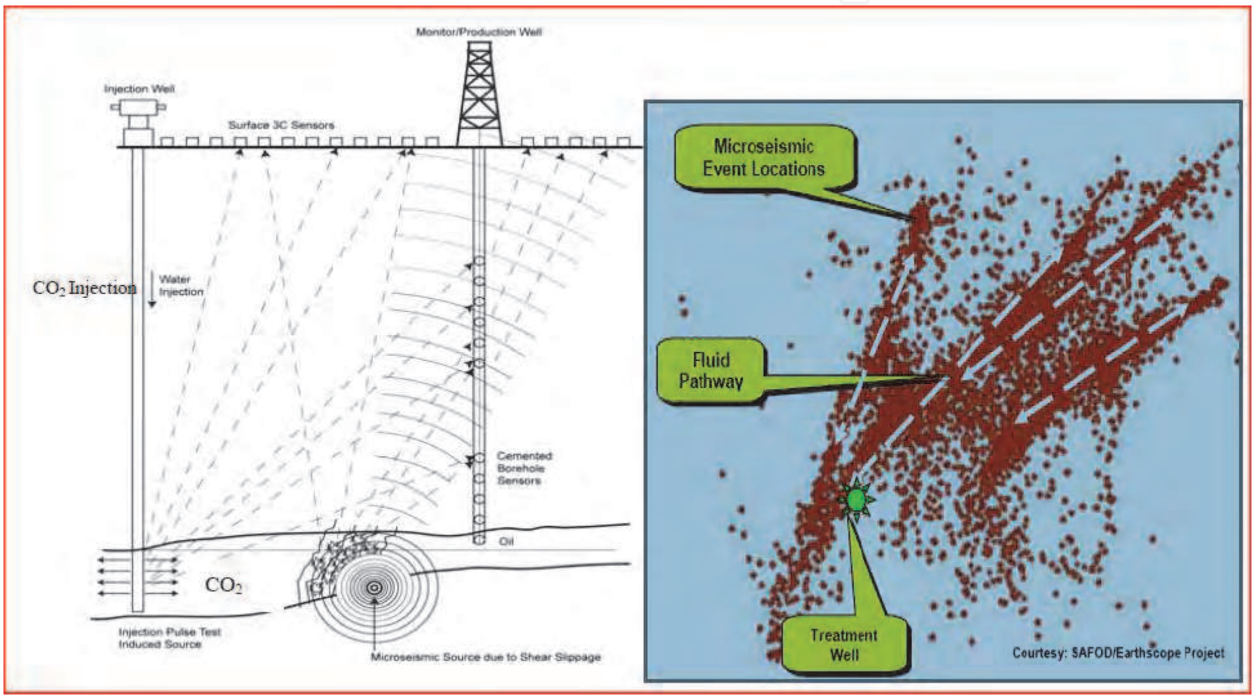


Fig. 6. An example of fluid pathway monitoring by micro-seismic technique with seismic events (Dasgupta, 2006).

Although the example of micro-seismic in Figure 6 is at the surface, micro-seismic also can be used in downhole if it is required (DTI, 2005). The micro-seismic technique is mostly used in the low permeability reservoirs where the pressure changes are sensitive according to the $CO_2$ injection ($CO_2$STORE, 2007).

**Multi-component Seismic Technique**: The main idea of this method is to introduce longitudinal (P-) waves and transverse (S-) waves to survey more fluid and reservoir properties (Davies et al., 2004). For the monitoring onshore, there are three polarised s-wave sources and three-component geophones for full-wave survey with total nine-component data. For an offshore purpose, because the s-waves do not propagate through water, converting waves from S- to P- wave is needed to map the sea bed by sensor package. S-waves are more sensitive to fractures than P-waves but less effective to the fluid content than P-waves (DTI, 2005). As a potential application, this technique was introduced to the Vacuum, Weyburn, and West Queen fields as an critical method to monitoring $CO_2$ movement (Benson, 2010).

**Well-based Seismic Technique**: The seismic technique with receivers in the wellbore are named as well-based seismic technique. The seismic sources can be at the surface (named as downhole method) or from another wellbore (named as cross-hole method). Downhole seismic survey is a simple and cheap method since it requires only one borehole. The basic idea is to record the velocity profiles from a fixed seismic source point to the downhole points by gradually moving down in the wellbore. The reservoir properties are interpreted from these records. Crosshole requires at least two wells around to the $CO_2$ storage site. The seismic sources are mounted in one wellbore and receivers are in the other one. Velocity and attenuation variations according to the travel-time and seismic amplitude changes, are mapped and analyzed for $CO_2$ plume and pressure change between two wells (DTI, 2005). An example of crosshole seismic used in Frio-II for $CO_2$ plume monitoring is demonstrated in Figure 7 (Daley et al., 2007; Freifeld et al., 2008). Moreover, this technique is useful to assess how much pore space is effective for the $CO_2$ storage.

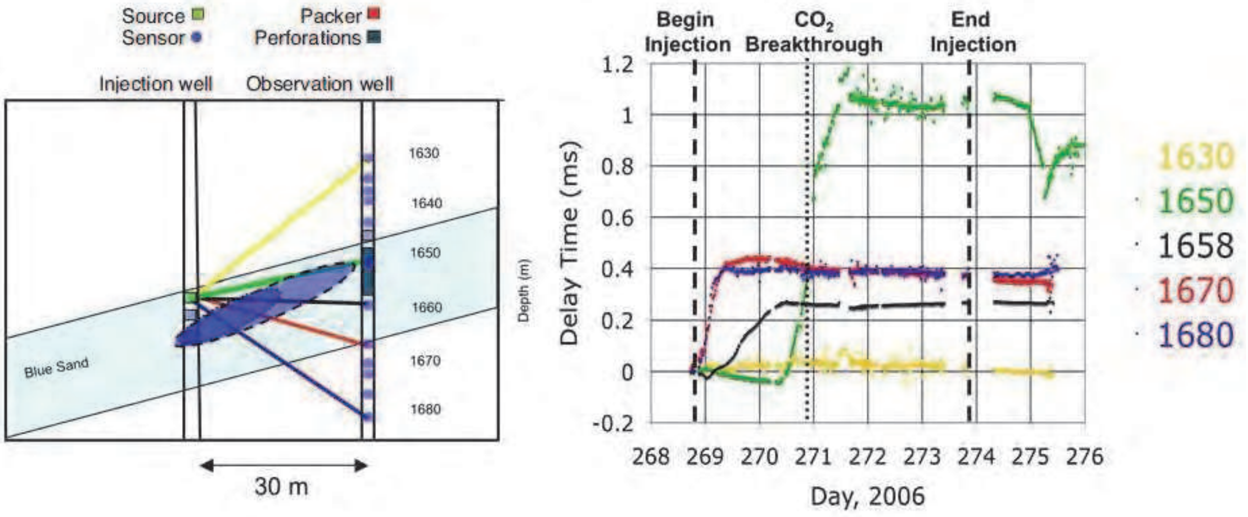


Fig. 7. An example of crosshole seismic used in Frio-II for $CO_2$ plume monitoring. The figure was modified by Freifeld et al. (2008) based on the original work (Daley et al., 2007). Two eclipses on the left are the $CO_2$ for one day (inner) and two day (outer) after injection. The measurements of delay time for five sensor depths (1630, 1650, 1658, 1666, and 1680 meters ) are on the right plots. These plots show the progressively later increasing in delay time with decreasing depth except the shallowest depth 1630 meters during the monitoring period.

Depending on the site, beyond two receiver wellbores can be located near the energy sources wellbore to detect $CO_2$ plume around the whole storage reservoir. A scheme with four monitoring wells around the injection well (the distance range from injection well to monitoring wells is 40 to 120 meters) was designed to demonstrate $CO_2$ monitoring with a small scale injection at a rate of 10-48 tonnes per day in Nagaoka, Japan by Kikuta et al. (2004). The results confirm the benefits of the crosshole seismic technique that even a small amount (hundreds to thousands of tonnes ) of $CO_2$ can be detected. However, the $CO_2$ beyond the region of the system of the seismic source and receive wells cannot be detected. This is the main limitation of the well-based techniques.

**Vertical Seismic Profiling (VSP)**: This is another method usually using borehole to vertically monitor the property variations of the reservoir and fluid. Mostly, the $CO_2$ plume and pressure changes due to $CO_2$ injection can be well detected in- and post-injection periods. This technique show the good abilities in the storage site with big vertical differences of geological characteristics because the down-going wave and up-going wave can be separated by VSP.

As a summary, seismic technologies play a curial role in the $CO_2$ monitoring for leakage and risk assessment especially in- and post-injection period. Most of the technologies stated above can be used at the surface or subsurface through borehole based on the specific $CO_2$ monitoring site. The technologies can be cooperated together for monitoring purpose from deep to shallow, in-injection to post-injection, small scale to large scale. Even based on the specific conditions of the storage site, the properties of the seismic technologies, such as resolution of acoustic imaging and amplitude of the seismic source can be changed as various seismic techniques, such as high resolution acoustic imaging (DTI, 2005). More applications of these technologies will be stated in the section 3 Field Applications of Monitoring Technologies.

### 2.2 Electromagnetic technologies

The idea of the electromagnetic technologies is to transmit an electric (magnetic) source to the $CO_2$ storage site by grounded dipole and receive response of the source for figuring out the conductivity by contrasting the response difference from subsurface. Because the resistivity of $CO_2$ is lower than water, the conductivity change due to $CO_2$ injection can be detected by the electromagnetic technologies. A resistivity results of the $CO_2$ and water were confirmed under the reservoir pressure and temperature in the laboratory tests by Borner et al. (2010) as shown in Figure 8. The conclusion of the experiments indicates that the resistance decreases with $CO_2$ injection increasing. The pure $CO_2$ does not show any relevant electric conductivity even when the pressure increased to 130 bar (Borner et al., 2010).

Based on the resistance differences between $CO_2$ and others in the reservoir, a typical scheme of the electromagnetic method for $CO_2$ plume monitoring is suggested in Figure 9 (LLNL, 2005). In this scheme, electrical current being offered between two casings for mapping voltage distribution is measured on the remaining casings, repeating the mapping process with different pairs of casing until the whole $CO_2$ volume being figured out (LLNL, 2005).

Field tomographic data was acquired at the site in April 2001, October 2001, July 2002, and October 2003. Due to some reasons, the $CO_2$ injection was stopped in December 2002. The results of $CO_2$ plume are provided in Figure 11 based on the proposed system in Figure 10 (Kirkendall & Roberts, 2004). These observations are time-lapse set of two-dimensional images between transmitting and receiving in Figure 11. A) is the background distribution before $CO_2$ injection. B) is the imaging with five months of $CO_2$ injection. And C) is the difference image between A) and B). This difference clearly shows the $CO_2$ movement where located in the top left from injection perforation which is red color areas. Dark blue is the replaced water by injected $CO_2$. The region with yellow color is distinguished as oil movement. These conclusions confirmed the laboratory tests that is the resistivity values playing crucial in brine delineating from $CO_2$ and oil. Moreover, $CO_2$ and oil also can be recognized by the similar method based on their resistibility (Kirkendall & Roberts, 2004).

Moreover, Ishido published a direct correspondence between water saturation change and electric field amplitude change by Ishido & Mizutani (1981). Electromagnetic technology was

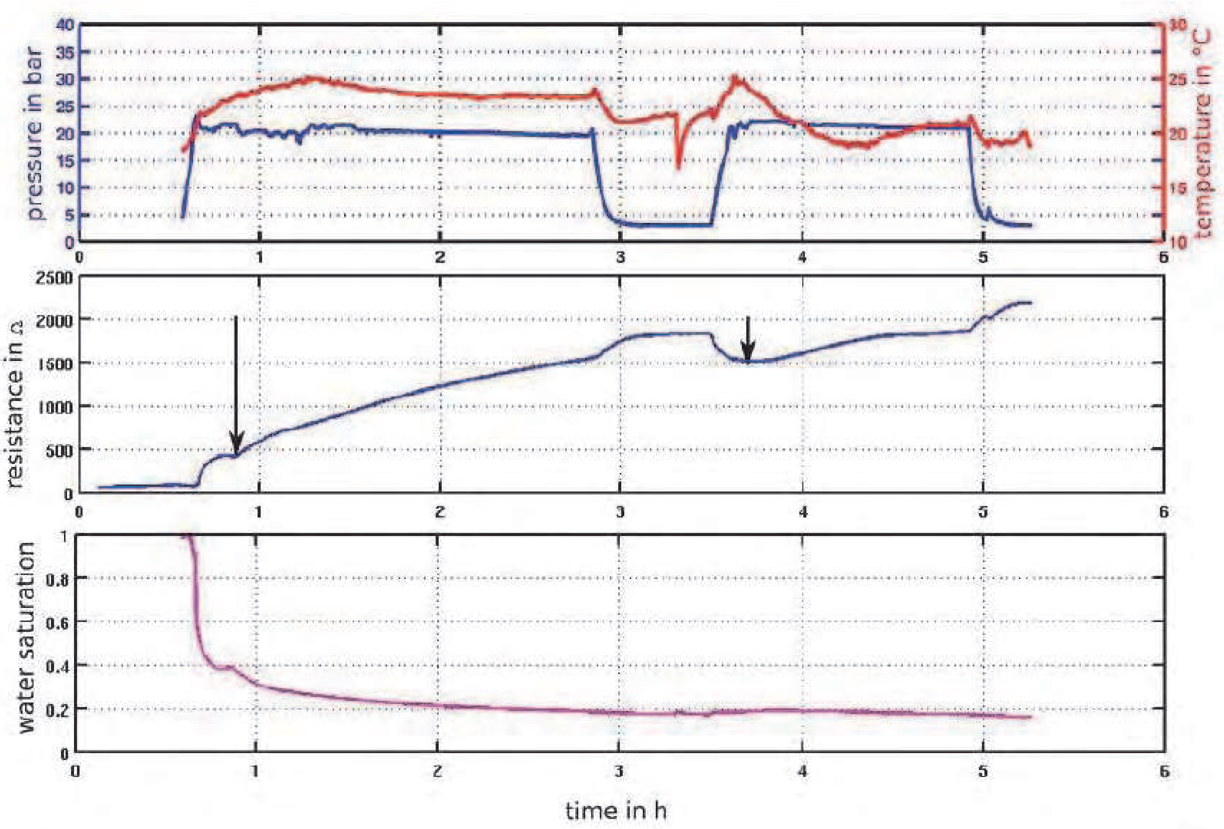


Fig. 8. Resistance results of the $CO_2$ and water under the reservoir pressure and temperature in the laboratory tests by Borner et al. (2010). Two arrows are the start point of $CO_2$ injection. With more $CO_2$ injection, the resistance becomes higher.

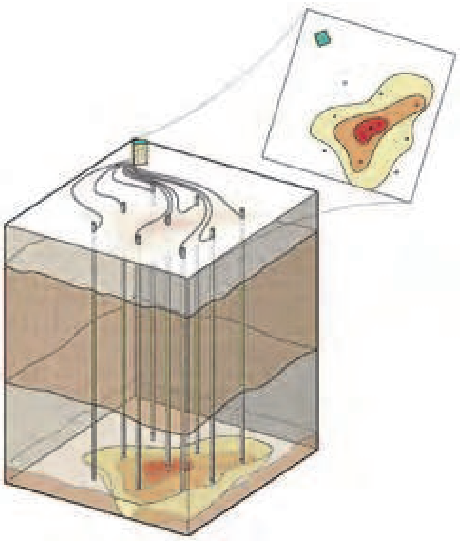


Fig. 9. A typical scheme of the electromagnetic method for $CO_2$ plume monitoring by measuring the electrical resistivity distribution in the subsurface (LLNL, 2005).

reported as monitoring method to detect $CO_2$ leakage through permeable fractures by various frequencies electromagnetic sources (Mikhailov et al., 2000). Electromagnetic technologies indicate the ability to monitor offshore $CO_2$ storage seabed at depths up to several kilometers.

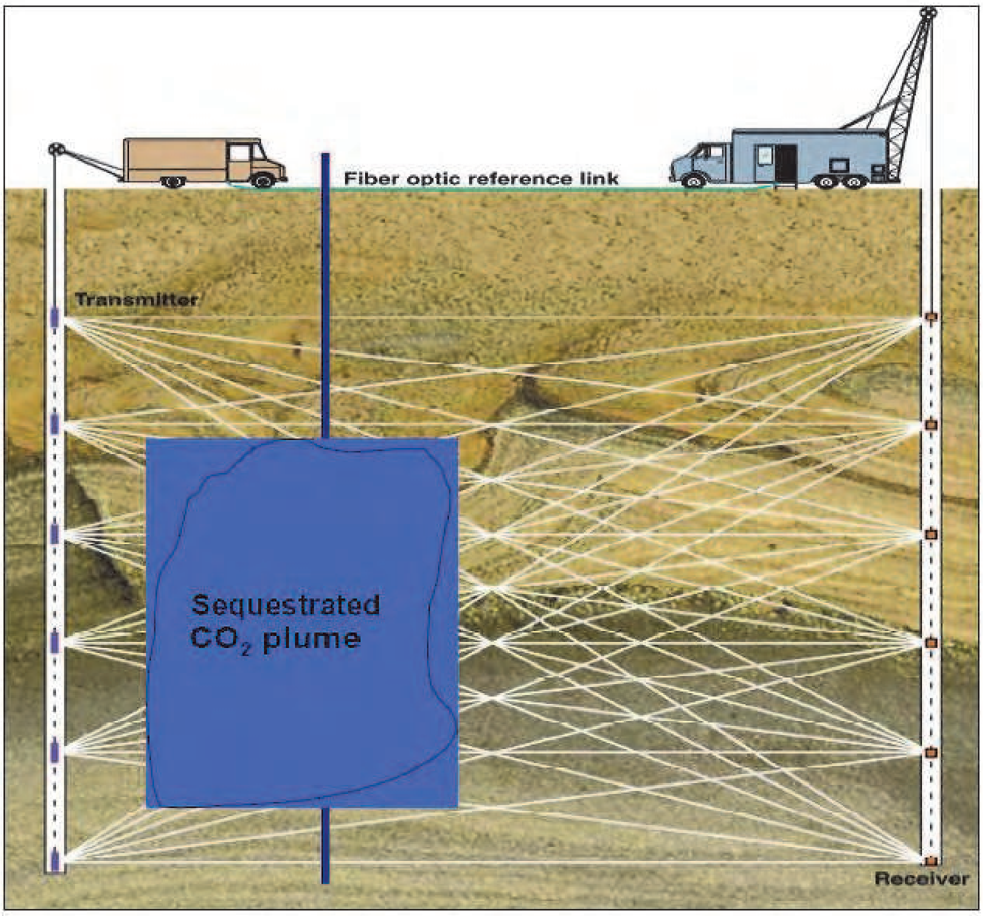


Fig. 10. The system used for $CO_2$ plume mapping in Lost Hills anticline in San Joaquin Valley, California by electromagnetic technologies (Kirkendall & Roberts, 2004).

For this application, electromagnetic technique is called seabed-logging (Johansen et al., 2005). However, the work of Johansen et al. (2005) suggested that seabed logging was supposed to work at least 300 meters of deep water for obtaining enough mapping signals based on the current study.

### 2.3 Gravimetric technologies

Gravimetric technologies can detect variations of the rock and fluid density due to $CO_2$ injection in the subsurface through measuring the gravitational acceleration. As reported by Goldberg (2011), a typical workflow of the techniques for downhole measurement includes the following:

- Determine the various vertical depths according to the monitoring task;
- Install gravimetric sensors with sidewall of the borehole in the geological formations;
- Measure the local gravitational field or gravity gradient as the baseline gravimetric data;
- Measure the local gravitational field or gravity gradient again as post-baseline data with time intervals from baseline measurement;
- Quantify the difference between baseline data and post-baseline data to monitoring $CO_2$ movement on both vertical and horizontal directions.

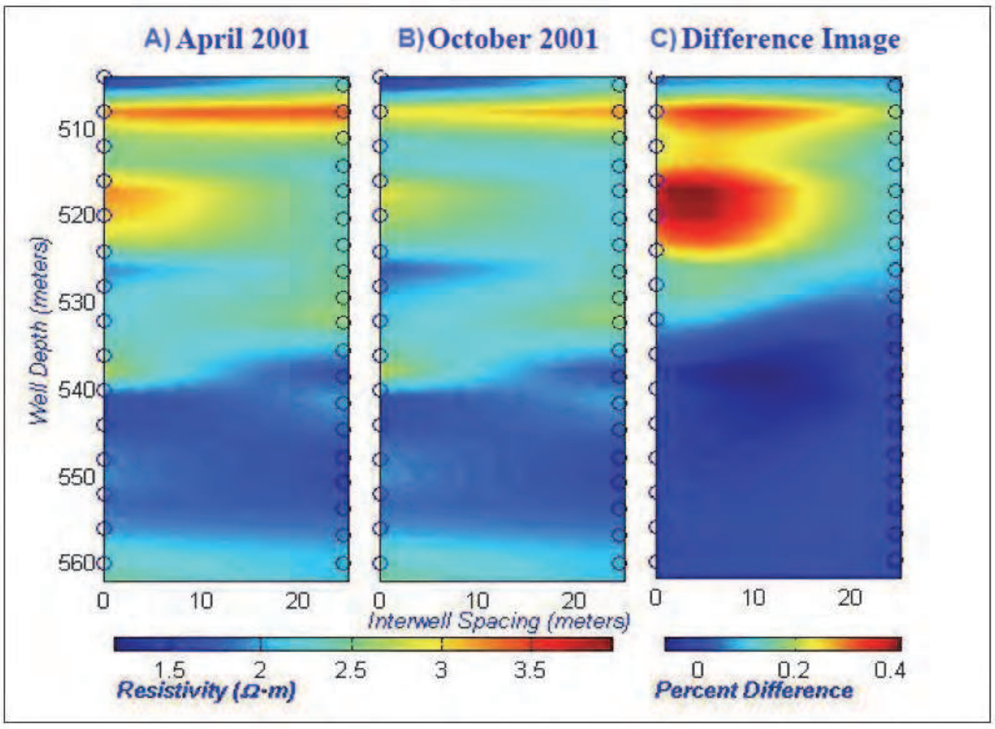


Fig. 11. Field tomographic data was acquired by electromagnetic technique in Lost Hills anticline in San Joaquin Valley, California in four date periods, April, 2001, October, 2001, July, 2002, and October, 2003. A) is the background distribution before $CO_2$ injection. B) is the imaging with five months of $CO_2$ injection. And C) is the difference image between A) and B) (Kirkendall & Roberts, 2004).

Moreover, the author pointed out a range of the density changes of $CO_2$-aquifer over depth (Goldberg, 2011). The density contrast is around 500 $kg/m^3$ at the shallow depth within 1000 meters. With depth increases to 2500 meters, $CO_2$ will be in a supercritical phase. Correspondingly, the density difference decreases to about 200 $kg/m^3$. If deeper than 2500 meters, the density of $CO_2$ becomes heavier than aquifer; the difference is about 40-50 $kg/m^3$. Regarding the minimum sensitivity (mostly is around 10 $\mu Gal$) of gravimetric sensor, these contrasts over the depth are enough to be measured of gravimetric technologies (Goldberg, 2011).

Estimating the amount of dissolved $CO_2$ is one of the challenge problems because some technologies, such as seismic are not effective for such changes. However, gravimetric technologies can monitor these amount of changes by quantifying mass differences between baseline data and multiple post baseline data ($CO_2$STORE, 2007). Moreover, gravimetric measurement can be installed both at the surface and downhole for onshore and offshore monitoring purposes (Chadwick et al., 2009; $CO_2$STORE, 2007; Stenvold, 2008).

### 2.4 Surface and near surface technologies

Compared to the technologies stated above, this section more focuses on the shallow to surface monitoring. There are many technologies for surface and near-surface which mainly include soil flux monitoring based on the chamber equipments (LI-COR Bioscience, 2004; Madsen et al., 2009) or enhanced vent-based scheme (Liu, 2010; Liu et al., 2009), micrometeorological flux monitoring (Burba & Anderson, 2010; Madsen et al., 2009), tracers monitoring (Phelps et al., 2007; Wells et al., 2007), surface deformation monitoring (Davis & Marsic, 2010b; Sweatman & McColpin, 2009), surface water monitoring (Darby et al., 2008; Emberleya et al., 2004).

### 2.4.1 Chamber-based soil $CO_2$ flux monitoring

Chamber-based soil $CO_2$ flux measurement is a direct method at the surface to monitor $CO_2$ leakage. Roughly, there are two types of chambers named as closed top and open top as reported in the papers (Edwards & Riggs, 2003; LI-COR Bioscience, 2004; 2011; Madsen et al., 2009; Vanaja et al., 2006). In view of the applications to the field monitoring, closed-chambers appears to have wider usage than open ones. As an example, closed-chamber methods developed by LI-COR Bioscience are reviewed in this section. A schematic of this chamber is shown in Figure 12 (LI-COR Bioscience, 2004; Madsen et al., 2009). This system includes two main parts as closed-chamber and analyzer. The small portion of air is collected firstly in the chamber, and then piped to the analyzer for $CO_2$ flux monitoring by an infrared gas analyzer.

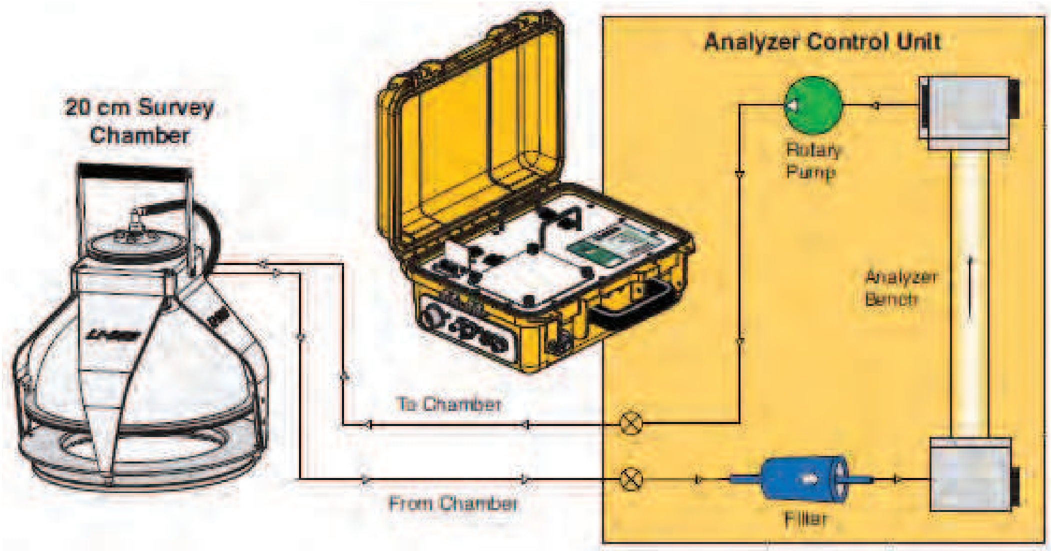


Fig. 12. An example of closed-chamber schematic (LI-8100) developed by LI-COR Bioscience (LI-COR Bioscience, 2004).

For this type of instrument, four main criteria were suggested by LI-COR Bioscience (2004) for accurate measurement: firstly, keeping the pressure equilibrium inside the chamber; secondly, ensuring a good mixing of the air in chamber; thirdly, handling an altered diffusion gradient inside the chamber; and the last one is to minimize the disturbance from the environment (LI-COR Bioscience, 2004). The new version of instruments with solution of such criteria has been applied to field tests, such as Soybean field in Nebraska, Central Appalachian Coal Seam Project of the Southeast Regional Carbon Sequestration Partnership, $CO_2$SINK and Midwest Geological Sequestration Consortium Illinois Basin-Decatur Illinois Site Project (LI-COR Bioscience, 2004; 2011; Madsen et al., 2009). One of the $CO_2$ soil flux monitoring results with fluctuated temperature in Soybean field in Nebraska is shown in Figure 13 (LI-COR Bioscience, 2004). The diurnal soil $CO_2$ flux was observed in July, 2006. The flux range varying from 2 to 7 $\mu mol(m^{-2}s^{-1})$ was comparable with other published data at the same location (LI-COR Bioscience, 2004).

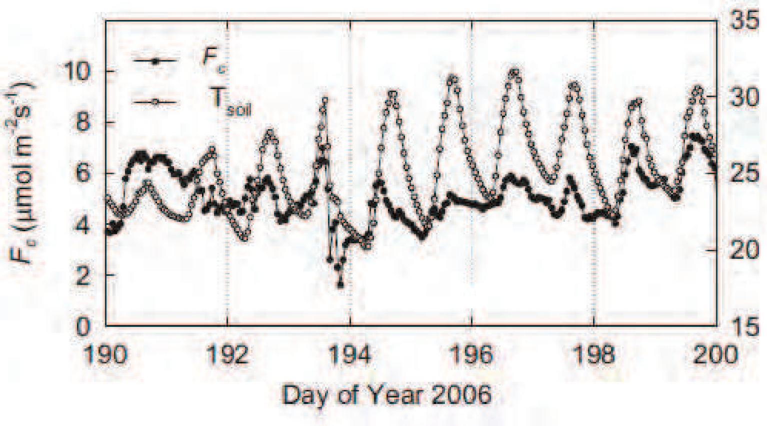


Fig. 13. Soil $CO_2$ flux monitoring results in Soybean field at the University of Nebraska-Lincoln Agricultural Experimental Station Near Mead in Nebraska (LI-COR Bioscience, 2004).

### 2.4.2 One-way vent-based $CO_2$ flux detection

Regarding to the $CO_2$ monitoring in the near-surface, it is important to realize that the $CO_2$ flux is not only affected by geological properties but also by barometric pumping. Periodic variation of the atmospheric pressure drives a natural "breathing"between the atmosphere and sub-surface (Martinez & Nilson, 1999; Neeper, 2001; Olson et al., 2001; Tillman & Smith, 2005). With the periodic increase of barometric pressure, gas is pushed downward into the soil; this is known as "inhaling". Conversely, "exhaling"occurs when the soil pressure is higher than the barometric pressure, which drives the air-flow upwards (Choi & Smith, 2005; Martinez & Nilson, 1999; Neeper, 2001; SEAI, 1996). As an example, hourly observations of pressure and the air flowrate during a 4-day period at Castle Airport in the summer of 1998 (NFESC, 2004) is shown in Figure 14. Although the records are not strictly periodic, the diurnal nature in the pressure variation is obvious. Figure 15 is a modeling demonstration of "air breathing"with a periodic sinusoidal barometric change (Liu, 2010).

To predict the $CO_2$ ground surface flux with considering barometric pumping to determine if this quasi-periodic pressure variation significantly affects near-surface $CO_2$ in the vadose zone, a scheme was suggested to address the effect of a one-way vent valve on the control of $CO_2$ flux during barometric pumping. In many leakage scenarios, $CO_2$ will escape at low concentrations over wide areas. The purpose of the suggested scheme is to concentrate the low $CO_2$ flux leakage from a large area so that the number of detectors and their required sensitivity can be reduced for the detections (Liu, 2010; Liu et al., 2009).

An example was given in Figure 16 based on the proposed scheme. The vent valve system includes a one-way vent valve, buffer (plenum), and membrane for coverage of the surface for impermeable purpose. One-way vent valve is controlled by the pressure difference between subsurface gas pressure and barometric pressure as shown in Figure 16. The domain used in the tests is the 20 × 20 meter axi-symmetric two-dimensional geometry, including two soil layers. The thickness of topsoil is 3.5 meters from the surface. Another 16.5 meters is cobble.

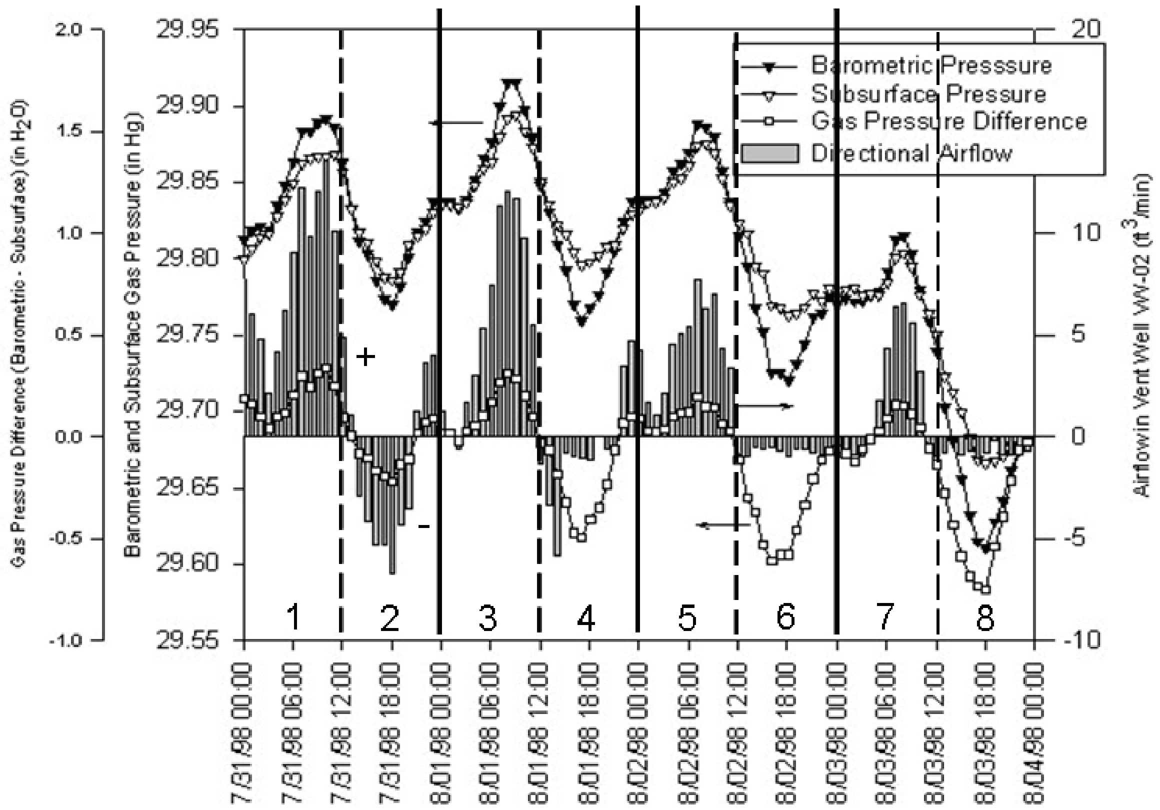


Fig. 14. Airflow, barometric, and subsurface pressures during 4 days monitored through a well at Castle Airport (NFESC, 2004).

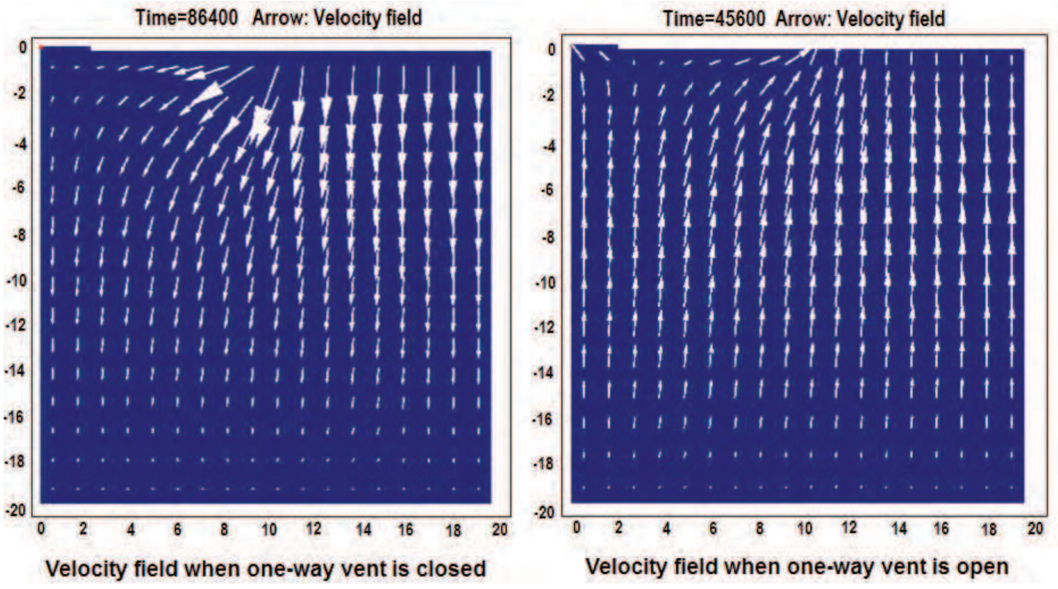


Fig. 15. Example of velocity fields controlled by one-way vent control with barometric pumping (Liu, 2010).

The $CO_2$ source point is located at 5 meters deep marked by the red dot, and the water table is 4.25 meters deep along the white line in Figure 16. The region above the water table is the vadose zone. The right section of Figure 16 is the scheme and grid used in the simulations (Liu, 2010; Liu et al., 2009).

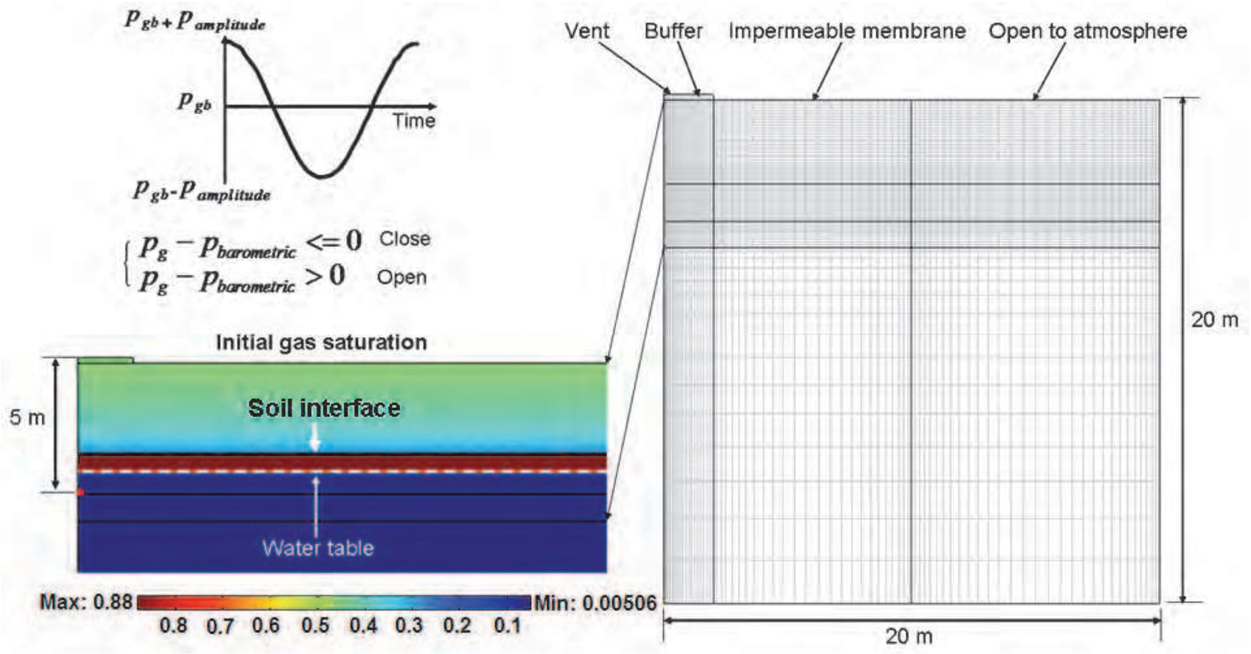


Fig. 16. Domain and the vent valve system coupled on the top boundary for investigation of the proposed method. The red point is the $CO_2$ source point. Besides, the soil interface line and the horizontal cross lines are for local grid refinement while the verticals are boundaries of the buffer and the impermeable membrane (Liu, 2010; Liu et al., 2009).

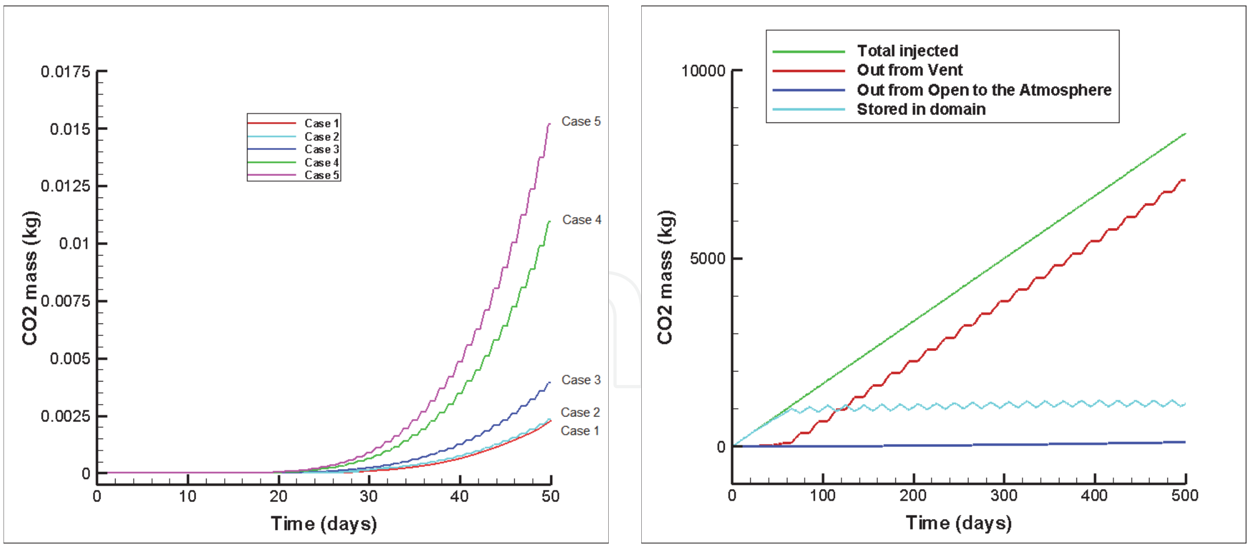
To demonstrate on how the proposed scheme enhances $CO_2$ leakage monitoring is effective, a series of the cases was designed in Table 1 for comparisons of the total $CO_2$ mass out from the one-way vent in Figure 17(a).

| Case No. | Barometric Pumping | Impermeable Membrane (m) | Vent | Buffer & Size (m) | Δ P (Pa) | Period (day) |
|---|---|---|---|---|---|---|
| 1 | no | no | no | no | no | no |
| 2 | yes | no | no | no | 800 | 1 |
| 3 | yes | no | yes | no | 800 | 1 |
| 4 | yes | 10 | yes | no | 800 | 1 |
| 5 | yes | 10 | yes | yes, 0.2 | 800 | 1 |

Table 1. Summarized Investigation Cases

Through comparisons in Figure 17(a), the proposed concept was confirmed to use an impermeable membrane and a one-way vent valve to concentrate gas from a large region at the vent so that fewer sensors, and sensors of lesser sensitivity, could be used for detection of $CO_2$ leaking from geological storage. This is the reason why the accumulated $CO_2$ mass out from the vent is the highest than the other 4 cases. Figure 17(b) shows the details on why the sensor on the vent was easier and quicker to catch $CO_2$ leakage because high percentage (more than 85%) of total leaked $CO_2$ was collected and flowed out from the vent.

Moreover, another 22 cases (a total of 27 cases) were designed to address the effects from the other related factors: the properties of barometric pressure (amplitude and period), variations



(a) Comparisons among five cases (b) Comparisons among $CO_2$ mass balance

Fig. 17. Comparisons of the $CO_2$ mass out from the vent (Liu, 2010).

of impermeable membrane and buffer zone size, and meteorological phenomena (rainfall and wind) under the various soil permeability and leakage source rate. All of the tests draw the consistent conclusion that the proposed scheme, one-way vent valve system by Liu (2010), is efficient at the near-surface $CO_2$ flux monitoring.

### 2.4.3 Eddy covariance based $CO_2$ flux monitoring

The first eddy covariance method was suggested by Swinbank Swinbank (1951). This methods was proposed to directly measure the detailed structure of temperature, vapor pressure, and total wind speed and its vertical component of the air passing a fixed point, which are brought about by eddy movement in the lower atmosphere through a apparatus (Swinbank, 1951). This method relies on a combination of wind velocity and $CO_2$ concentration measurements based on the derivation of the turbulent eddies and corresponding scalar from the fast measurement average values (Burba & Anderson, 2010; LI-COR Bioscience, 2006). Recent years, this method has been applied to $CO_2$ leakage monitoring in the atmosphere (Benson, 2006; Cooka et al., 2004; Goulden et al., 1996; Lewicki et al., 2009; LI-COR Bioscience, 2004; 2006; 2011; Miles et al., 2004). As examples, $CO_2$ emissions were monitored in the Barrow Island site in Alaska and Willow Creek site in Wisconsin in 2002 and 2005 respectively (Benson, 2006; Cooka et al., 2004). The conclusions indicate that the resolution of proposed instruments show the good abilities in $CO_2$ monitoring with excluding the natural background fluxes (Benson, 2006; Cooka et al., 2004; Miles et al., 2004).

### 2.4.4 Surface deformation monitoring technologies

Because of $CO_2$ injection and related extraction of fluids, the pressure underground changes which means that the corresponding strain changes and results in the displacement. Surface deformation monitoring technologies are based on measuring this displacement (swelling and shrinkage) for the purpose of monitoring (Davis & Marsic, 2010a; Sweatman & McColpin, 2009). The technologies integrate three parts, which are satellite-based interferometric synthetic aperture radar (InSAR), surface tiltmeters, and differential global positioning system (DGPS). InSAR is used to provide periodic updates of the ground deformation within a typical coverage area about 10,000 $km^2$ by imaging large swaths of the earth's surface (Davis & Marsic, 2010a; Davis et al., 2008; Du et al., 2005; Kherroubi et al., 2009; Lewicki et al., 2009; Sweatman & McColpin, 2009). Tiltmeter is built with a highly sensitive electrolytic bubble level to measure tilt movements in a one nanoradian of radian level. DGPS monitoring is usually used to supply InSAR and tiltmeter arrays in acquisition areas. At least two GPS receivers and sophisticated Kalman filters are used to exam the horizontal and vertical motions in typical differential method. One receiver is placed in an area where non-deformation is a reference; another receiver(s) is located in the region(s) where the deformation needs to be monitored. The difference between the reference and the receiver is the surface deformation as shown in Figure 18. The accuracy of the surface deformation monitoring technologies can be millimeter level for both land and subsea instruments (Davis & Marsic, 2010c; Sweatman & McColpin, 2009). The applications of the technologies covered $CO_2$ storage in a coal-bed and deep saline aquifer (Davis & Marsic, 2010c; Sweatman & McColpin, 2009). Moreover, surface deformation monitoring technologies are useful in well stimulation efforts to map hydraulically created fractures (Gladwin, 1984; Sweatman & McColpin, 2009).

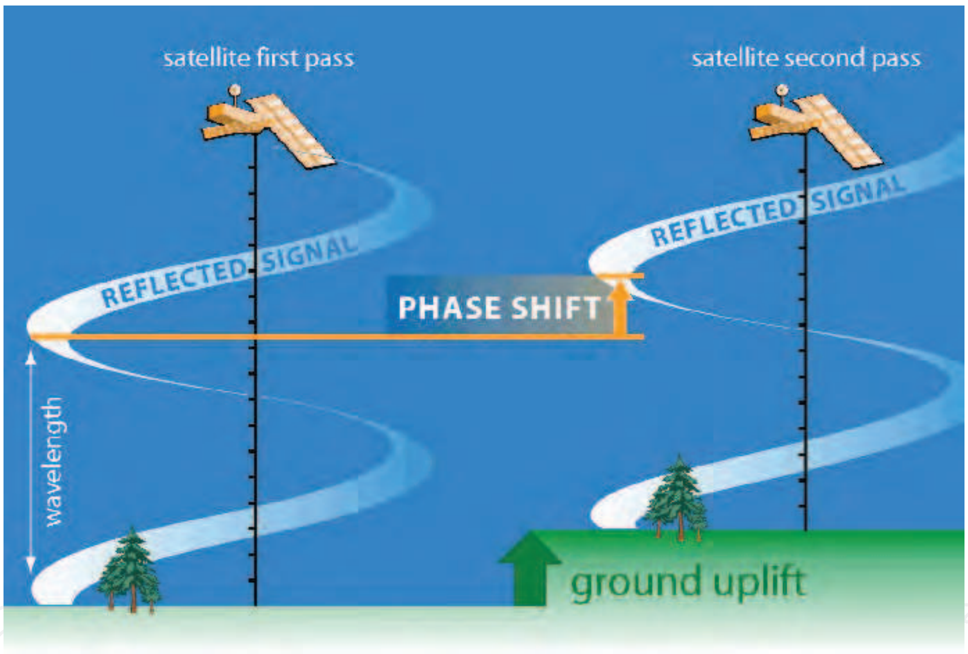


Fig. 18. Example of satellite-based InSAR technology for earth's surface deformation monitoring (Sweatman & McColpin, 2009).

### 2.4.5 Geochemical and tracer monitoring technologies

Geochemical monitoring involves measuring of the changes of the groundwater and/or associated gas content, such as $CO_2$, in and around storage site. The measurement is frequently done to detect the water composition differences, pH value changes, and electrical conductivity various, which is caused by the dynamic equilibrium of dissolution and mineralization systems, such as $Na^+ - Ca^{2+} - HCO3^{-1} - Cl^{-1}$. This detection also includes monitoring the changes of isotopic element, such as $^{13}C$, $^{14}C$, $^{18}O$, and $^{2}H$ (Benson & Gasperkova, 2004). The samples of the water can be collected from surface, wellhead, and/or downhole. These samples are usually taken from different locations in frequent time intervals. Similar to the time-lapse technologies, geochemical monitoring methods can be used in the whole process of $CO_2$ storage, such as pre-injection, injection, and post-injection. As an example, geochemical monitoring technologies have been used in the $CO_2$ storage in the Otway site in Australia (Caritat et al., 2009; Hortle et al., 2011). More than 70 groundwater compositions (elements/compounds) and seven isotopes from 28 sampling locations (stations) in various depths were tested. The preliminary results indicate that there is not much significant changes by contrasting the pre- and post-injection though some compositions varied a little based on some seasons. The mostly interesting factors, $HCO_3^-$ and pH values were shown in Figure 19 (Caritat et al., 2009; Hortle et al., 2011). It means that there is not any significant $CO_2$ leakage within the monitoring period.

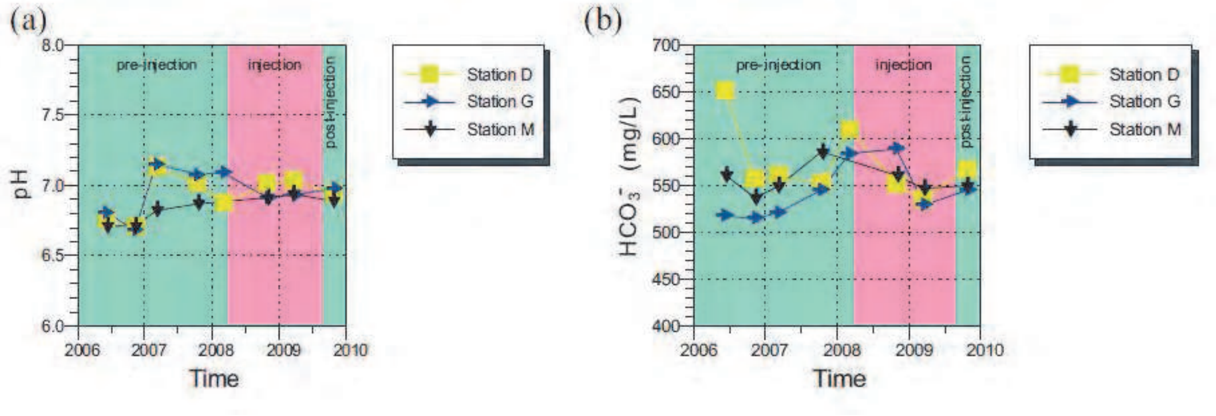
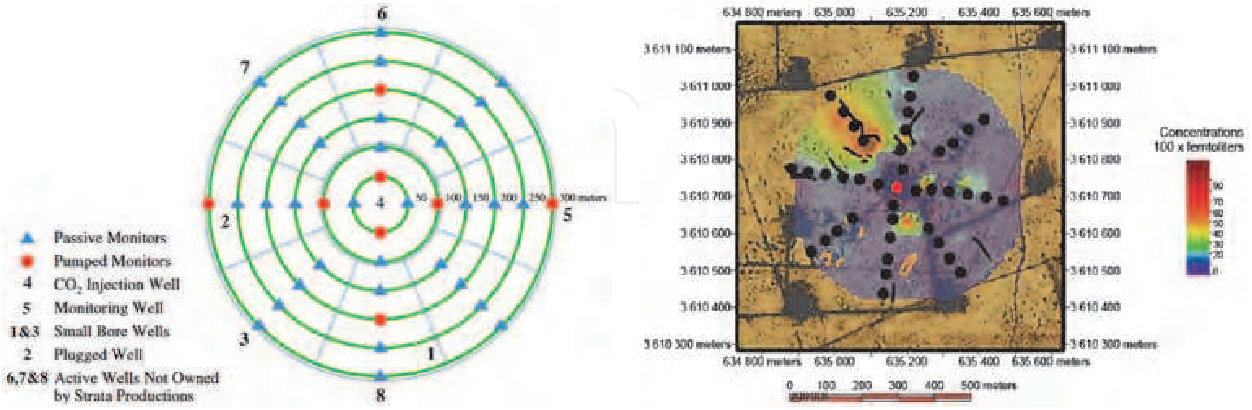
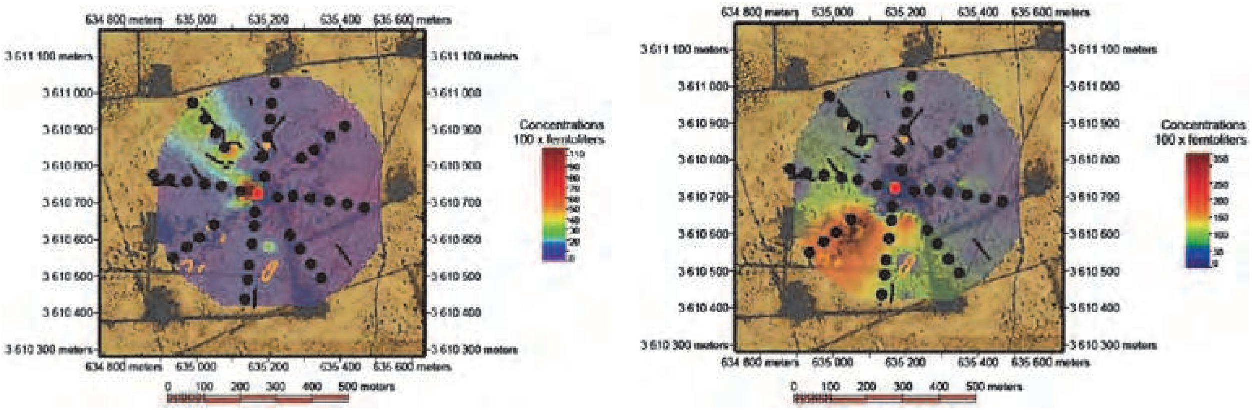


Fig. 19. The comparisons of $HCO_3^-$ and pH values from pre-injection, injection, and post-injection (Hortle et al., 2011).

Monitoring $CO_2$ by inspecting tracers is another option which can be used in the groundwater and vadose zone for the migration identification. The systemic study of the tracers in the field was discussed by Zemel (1995). The potential choices of the tracers include natural and artificial elements/compounds. Isotopes, such as C, O, H noble gases are the natural tracers, which have been widely used in different $CO_2$ storage sites (Bachelor et al., 2008; Stalker et al., 2009). $SF_6$, $CD_4$, and perfluorocarbons are good choices of artificial tracers (Hortle et al., 2011; McCallum et al., 2005). However, any tracer needs to be evaluated based on the occupational health, environmental safety, and suitability for the monitoring and analysis concerns (Stalker et al., 2009). As guidelines, a total of 13 points for tracer choice was suggested by Stalker et al. (2009). These points are briefly summarized as follows: 1. highly physical and chemical stability (without significant degrade, microbial, and reaction) for the selected $CO_2$ storage site (even under the high pressure and high temperature conditions); 2. Availability (even for large-scale of $CO_2$ injection) with competitive cost; 3. Collaborations in the $CO_2$ storage system which work with other tracers during different monitoring phases; 4. Easy detection and analysis during monitoring even in different monitoring depths with a background level of tracer self (Stalker et al., 2009). As part of the monitoring project of Zero Emissions Research and Technology (ZERT), a pilot site was selected in the West Pearl Queen, southeast of New Mexico, USA (Wells et al., 2007). In this monitoring program, several tracers, such as Perfluorocarbon tracers (PFTs), perfluoro-1,2-dimethylcyclohexane (PDCH), perfluorotrimethylcyclohexane (PTCH) and perfluorodimethylcyclobutane (PDCB) were used to detect $CO_2$ leakage in a series of six concentric circles (with different radius) centered injection well as shown in Figure 20(a). Authors reported a total of four sets of measurement data with the monitoring schematic design. As an example, only third set of the test results are cited in Figure 20 (Wells et al., 2007). One of the conclusions pointed out that these tracers show a excellent ability in $CO_2$ monitoring (Wells et al., 2007).



(a) Monitoring schematic design (b) PDCH concentrations



(c) PTCH concentrations (d) PDCB concentrations

Fig. 20. Orthophoto view of tracers concentration (third set of total four sets) measured over 54 days. Red dot is the injection well and black dots are the adsorbent tubes for sampling (Wells et al., 2007).

### 2.5 Terrestrial ecosystem monitoring technologies

$CO_2$ monitoring technologies in terrestrial ecosystems are not reviewed in this chapter since most methods are based on the $CO_2$ flux measurement and carbon biomass (Ebinger et al., 2001; Jacobs & Graham, 2000). However, the related knowledge are available through the publications by Betts et al. (2004); Brovkin et al. (2004); D. & E. (2003); Ebinger et al. (2001); Jacobs & Graham (2000); Lehmann et al. (2006); Wisniewski et al. (1993)

### 2.6 Cost of monitoring technologies

The cost for some monitoring technologies were summarized in Figure 21 by Benson & Gasperkova (2004). Besides, based on monitoring phases (pre-operational monitoring, operational monitoring, and closure monitoring), three options (low residual gas saturation saline formation (LRG), high residual gas saturation saline formation (HRG), and reservoir with EOR) of $CO_2$ storage were estimated by choices "basic monitoring package" and "enhanced monitoring package". The cost for "basic monitoring package" and "enhanced monitoring package" for three storage options are listed in Table 2 (Benson & Gasperkova, 2004; Zahid et al., 2011).

## 3. Field applications of monitoring technologies

The selection of monitoring technologies is specifically based on the $CO_2$ storage site, such as geological characteristics, which covers onshore or offshore, saline aquifers, or oil/gas reservoir. Moreover, the selection also depends on the monitoring phase, such as pre-injection, injection, and post-injection. In addition, the monitoring technologies selection starts from the beginning of $CO_2$ storage site selection. This is because two primary factors of storage capacity and cap-rock sealing ability are always investigated in the procedure of $CO_2$ storage from site characteristics, injection location determination, injection rate, and period to the monitoring detection during injection and post-injection. This procedure is also an optimization of determining low risk (such as leakage) with integrating injection location, injection rate, and injection period in the sink-seal system. Similarly, Seto & Mcrae (2011) suggested a framework for integrated monitoring design based on technologies and cost for risk reduction. In this section, only $CO_2$ monitoring technologies in several projects were reviewed to demonstrate how these technologies work in fields, rather than checking all injection and planned injection projects of worldwide in Figure 22.

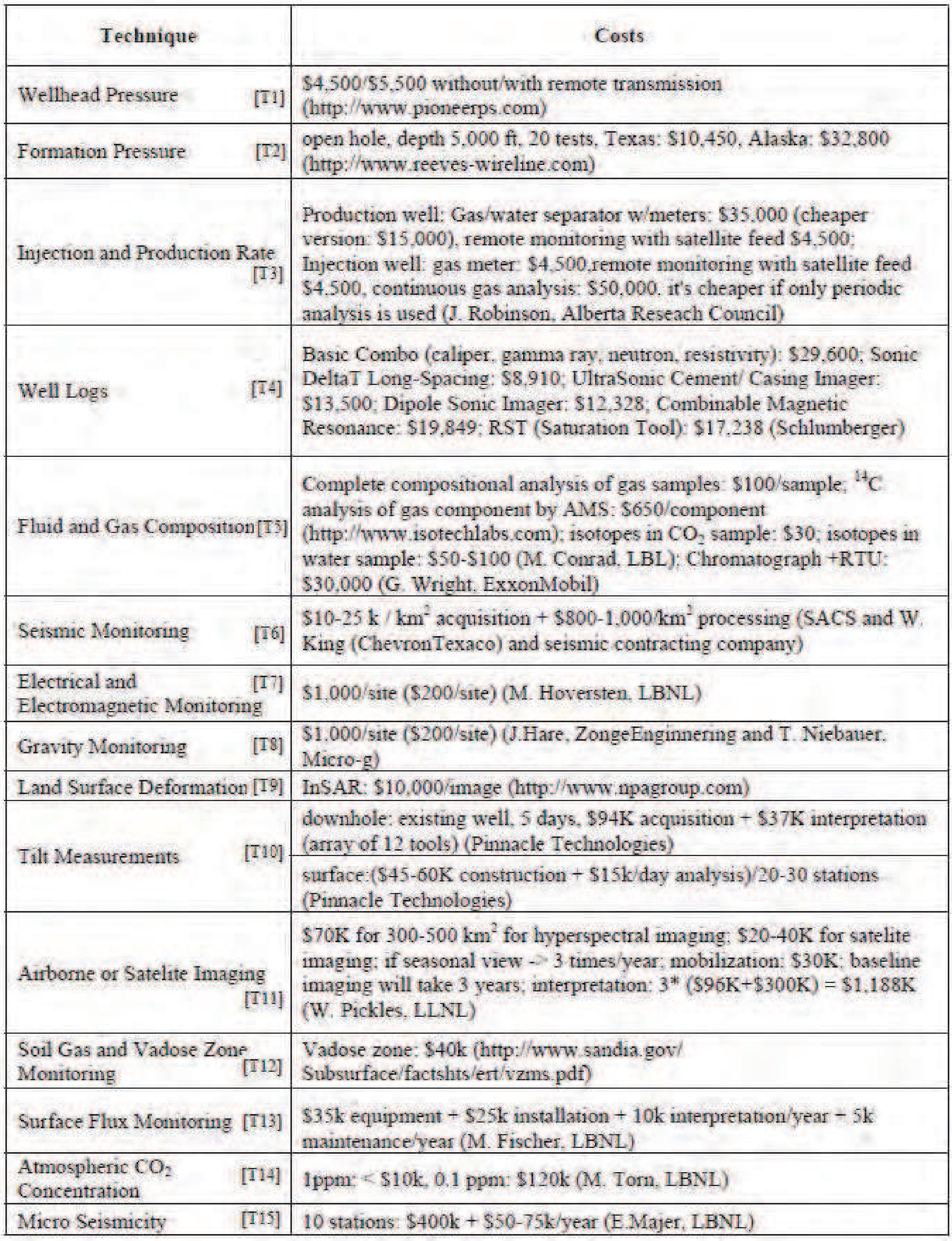
- **Sleipner**

The site at Sleipner, Norway North Sea has been developed for $CO_2$ storage by 1 Mt per year injection rate. The initial identification of the site for this project was investigated in 1994 and commenced with $CO_2$ by Statoil and the partners in 1996. The $CO_2$ injected in the storage formation "Utsira Sand" has been monitored by introducing seismic surveys, time-lapse seafloor gravity technologies, and surface/near-surface methods, such as soil gas and satellite remote sensing (Aleksandra et al., 2010; Arts et al., 2008). As an example, the results of 2D cross seismic surveys were shown in Figure 23 (Arts et al., 2008). By comparing the bright reflections in all images of Figure 23, the changes of the saturation due to $CO_2$ injection within the period is clear.

- **Salah**

The project of $CO_2$ storage located In Salah, Algeria, has been operated by BP, Sonatrach, and Statoil for 1.2 Mt per year of $CO_2$ injection rate in Jurassic saline formation around 1850 meters deep (Aleksandra et al., 2010; Mathieson et al., 2010). The technologies used for the $CO_2$ monitoring were summarized in Figure 24 (Mathieson et al., 2010).

Based on the technologies above, some monitoring results, such as surface deformation, satellite imaging, time lapse 3D seismic survey, and shallow aquifer tests were reported (Aleksandra et al., 2010; Chadwick et al., 2009; $CO_2$STORE, 2007; Onuma et al., 2009; Mathieson et al., 2011; 2010; Wildenborg, 2011). As an example, a ground deformation results from In Salah is shown in Figure 25 (Wildenborg, 2011). The period of the deformation tracking is from November 29, 2003 to August 29, 2009.



| Technique | Costs |
|---|---|
| Wellhead Pressure [T1] | $4,500/$5,500 without/with remote transmission (http://www.pioneerps.com) |
| Formation Pressure [T2] | open hole, depth 5,000 ft, 20 tests, Texas: $10,450, Alaska: $32,800 (http://www.reeves-wireline.com) |
| Injection and Production Rate [T3] | Production well: Gas/water separator w/meters: $35,000 (cheaper version: $15,000), remote monitoring with satellite feed $4,500; Injection well: gas meter: $4,500,remote monitoring with satellite feed $4,500, continuous gas analysis: $50,000, it's cheaper if only periodic analysis is used (J. Robinson, Alberta Reseach Council) |
| Well Logs [T4] | Basic Combo (caliper, gamma ray, neutron, resistivity): $29,600; Sonic DeltaT Long-Spacing: $8,910; UltraSonic Cement/ Casing Imager: $13,500; Dipole Sonic Imager: $12,328; Combinable Magnetic Resonance: $19,849; RST (Saturation Tool): $17,238 (Schlumberger) |
| Fluid and Gas Composition [T5] | Complete compositional analysis of gas samples: $100/sample; $^{14}C$ analysis of gas component by AMS: $650/component (http://www.isotechlabs.com); isotopes in $CO_2$ sample: $30; isotopes in water sample: $50-$100 (M. Conrad, LBL); Chromatograph +RTU: $30,000 (G. Wright, ExxonMobil) |
| Seismic Monitoring [T6] | $10-25 k / km$^2$ acquisition + $800-1,000/km$^2$ processing (SACS and W. King (ChevronTexaco) and seismic contracting company) |
| Electrical and Electromagnetic Monitoring [T7] | $1,000/site ($200/site) (M. Hoversten, LBNL) |
| Gravity Monitoring [T8] | $1,000/site ($200/site) (J.Hare, ZongeEnginnering and T. Niebauer, Micro-g) |
| Land Surface Deformation [T9] | InSAR: $10,000/image (http://www.npagroup.com) |
| Tilt Measurements [T10] | downhole: existing well, 5 days, $94K acquisition + $37K interpretation (array of 12 tools) (Pinnacle Technologies) |
| | surface:($45-60K construction + $15k/day analysis)/20-30 stations (Pinnacle Technologies) |
| Airborne or Satelite Imaging [T11] | $70K for 300-500 km$^2$ for hyperspectral imaging; $20-40K for satelite imaging; if seasonal view -> 3 times/year; mobilization: $30K; baseline imaging will take 3 years; interpretation: 3* ($96K+$300K) = $1,188K (W. Pickles, LLNL) |
| Soil Gas and Vadose Zone Monitoring [T12] | Vadose zone: $40k (http://www.sandia.gov/ Subsurface/factshts/ert/vzms.pdf) |
| Surface Flux Monitoring [T13] | $35k equipment + $25k installation + 10k interpretation/year + 5k maintenance/year (M. Fischer, LBNL) |
| Atmospheric $CO_2$ Concentration [T14] | 1ppm: < $10k, 0.1 ppm: $120k (M. Torn, LBNL) |
| Micro Seismicity [T15] | 10 stations: $400k + $50-75k/year (E.Majer, LBNL) |

Fig. 21. Cost evaluations for monitoring technologies (Benson & Gasperkova, 2004; Zahid et al., 2011). [T#] stands the index numbers which is used in the table 2.

| | Basic Monitoring Package | | | Enhanced Monitoring Package | | |
|---|---|---|---|---|---|---|
| Technologies | Saline Formation (LRG), $ | Saline Formation (HRG), $ | EOR Reservoir $ | Saline Formation (LRG), $ | Saline Formation (HRG), $ | EOR Reservoir $ |
| Pre-operational Monitoring | | | | | | |
| [T4] | 1,064,250 | 1,064,250 | 0 | 1,064,250 | 1,640,250 | 0 |
| [T1] | 55,000 | 55,000 | 0 | 55,000 | 55,000 | 0 |
| [T2] | 328,000 | 328,000 | 0 | 328,000 | 328,000 | 0 |
| [T3] | 550,000 | 550,000 | 0 | 550,000 | 550,000 | 0 |
| [T6] | 3,828,000 | 2,387,000 | 0 | 3,828,000 | 2,387,000 | 0 |
| [T7] | N/A | N/A | N/A | 225,000 | 225,000 | 360,000 |
| [T8] | N/A | N/A | N/A | 225,000 | 360,000 | 360,000 |
| [T15] | 475,000 | 475,000 | 475,000 | 475,000 | 475,000 | 475,000 |
| [T14] | 100,000 | 100,000 | 320,000 | 100,000 | 100,000 | 320,000 |
| [T13] | N/A | N/A | N/A | 700,000 | 700,000 | 700,000 |
| [T5] | N/A | N/A | N/A | 1,000,000 | 1,000,000 | 1,000,000 |
| Management (15%) | 960,038 | 743,888 | 119,250 | 1,282,538 | 1,066,388 | 482,250 |
| Sub-Total: | 7,360,288 | 5,703,138 | 914,250 | 9,832,788 | 8,310,638 | 3,697,250 |
| Operational Monitoring | | | | | | |
| casing Logs | N/A | N/A | N/A | 6,000,000 | 6,000,000 | 13,200,000 |
| [T6] | 9,493,000 | 9,493,000 | 15,840,000 | 9,493,000 | 9,493,000 | 15,840,000 |
| [T7] | N/A | N/A | N/A | 936,000 | 936,000 | 1,440,000 |
| [T8] | N/A | N/A | N/A | 936,000 | 936,000 | 1,440,000 |
| [T1] | 1,665,000 | 1,665,000 | 1,500,000 | 1,665,000 | 1,665,000 | 1,500,000 |
| [T3] | 3,351,000 | 3,351,000 | 6,450,000 | 3,351,000 | 3,351,000 | 6,450,000 |
| [T14] | 1,800,000 | 1,800,000 | 2,460,000 | 1,800,000 | 1,800,000 | 2,460,000 |
| [T13] | N/A | N/A | N/A | 4,800,000 | 4,800,000 | 4,800,000 |
| [T15] | 3,675,000 | 3,675,000 | 3,675,000 | 3,675,000 | 3,675,000 | 3,675,000 |
| [T5] | N/A | N/A | N/A | 570,000 | 570,000 | 570,000 |
| Management (15%) | 2,997,600 | 2,997,600 | 4,488,840 | 4,983,900 | 4,983,900 | 7,706,340 |
| Sub-Total: | 22,981,600 | 22,981,600 | 34,414,440 | 38,209,900 | 38,209,900 | 59,081,940 |
| Closure Monitoring | | | | | | |
| [T6] | 15,983,000 | 11,935,000 | 7,920,000 | 15,983,000 | 11,935,000 | 7,920,000 |
| [T7] | N/A | N/A | N/A | 1,519,000 | 1,125,000 | 720,000 |
| [T8] | N/A | N/A | N/A | 1,519,000 | 1,125,000 | 720,000 |
| [T1] | N/A | N/A | N/A | 277,500 | 277,500 | 1,250,000 |
| [T13] | N/A | N/A | N/A | 8,000,000 | 8,000,000 | 3,200,000 |
| [T5] | N/A | N/A | N/A | 950,000 | 950,000 | 380,000 |
| Management (15%) | 2,397,450 | 1,790,250 | 1,188,000 | 4,237,275 | 3,511,875 | 1,978,500 |
| Sub-Total: | 18,380,450 | 13,725,250 | 9,108,000 | 32,485,775 | 26,924,375 | 15,168,500 |
| Total Cost: | 48,722,338 | 42,409,988 | 44,436,690 | 80,528,463 | 73,444,913 | 77,947,690 |
| Total Cost at 10% discount | 13,697,010 | 12,023,781 | 12,683,389 | 20,927,707 | 19,250,724 | 23,319,093 |
| Total $CO_2$ | 2.58e8 | 2.58e8 | 2.58e8 | 2.58e8 | 2.58e8 | 2.58e8 |
| Cost/$CO_2$ Tonne | 0.189 | 0.164 | 0.172 | 0.312 | 0.284 | 0.295 |
| Discount Cost per $CO_2$ Tonne | 0.053 | 0.047 | 0.049 | 0.081 | 0.075 | 0.090 |

Table 2. Cost of monitoring packages modified from the works of Benson & Gasperkova (2004)

Fig. 22. Worldwide $CO_2$ injection and planned injection projects (Michael et al., 2009; 2010).

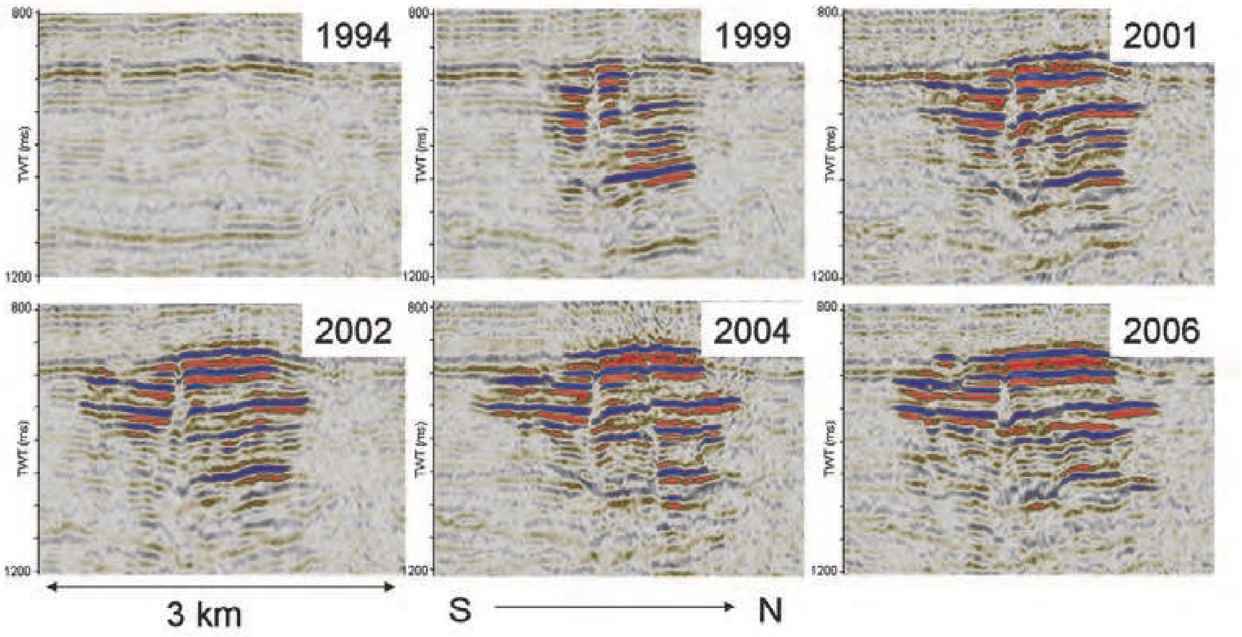
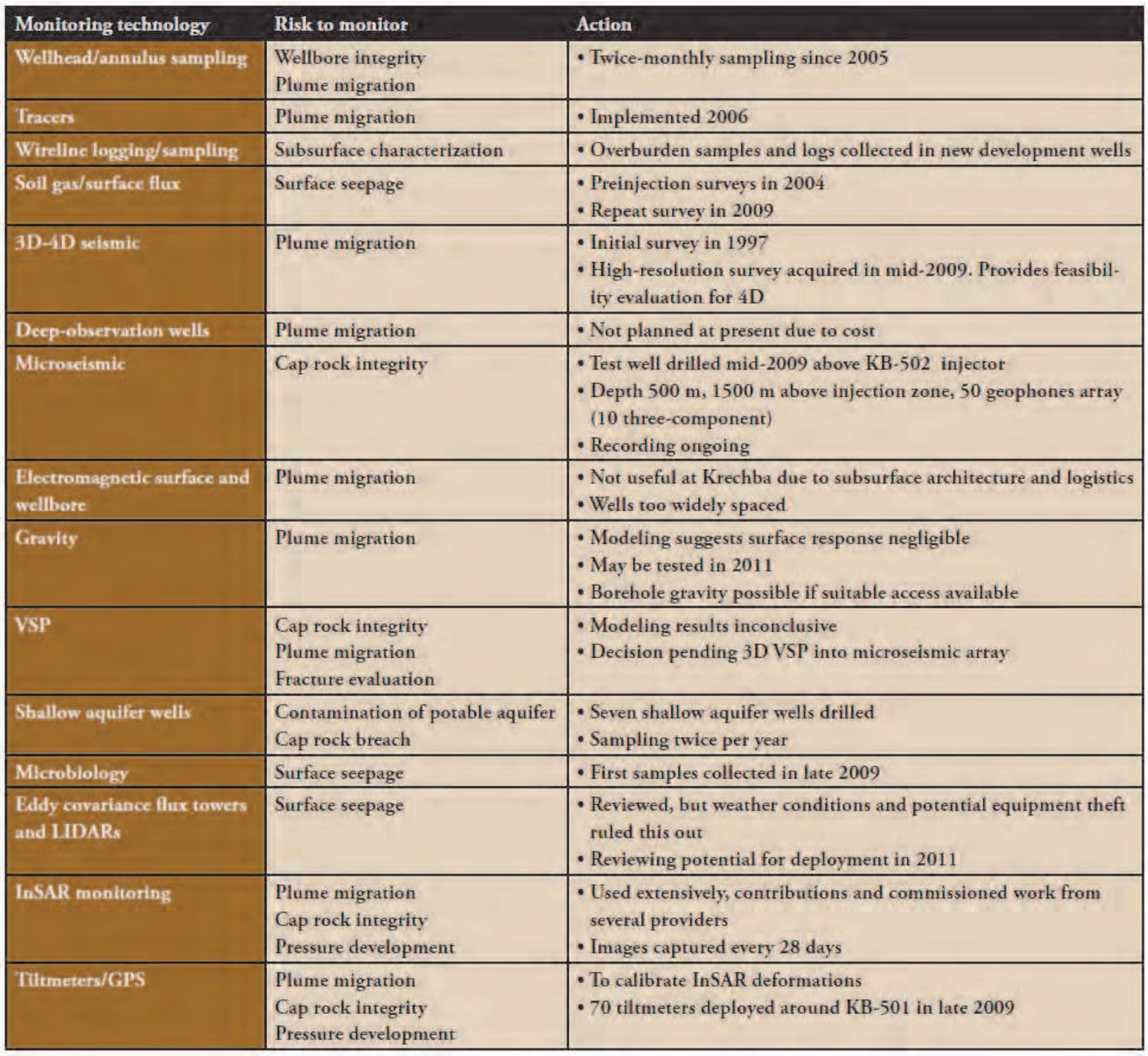


Fig. 23. 2D seismic cross view of the $CO_2$ storage site, Sleipner, Norway North Sea (Aleksandra et al., 2010; Arts et al., 2008).

- **Gorgon**

Storage $CO_2$ in the Gorgon field, Australia, was designed for large-scale of the $CO_2$ injection by the rate of 4.9 Mt per year. This project has been operated by Chevron, Royal Dutch Shell, and ExxonMobil and was approved for injection in August 2009. The technologies introduced for the monitoring include injection well monitoring by well head pressure, flow rate, and



| Monitoring technology | Risk to monitor | Action |
|---|---|---|
| Wellhead/annulus sampling | Wellbore integrity<br>Plume migration | • Twice-monthly sampling since 2005 |
| Tracers | Plume migration | • Implemented 2006 |
| Wireline logging/sampling | Subsurface characterization | • Overburden samples and logs collected in new development wells |
| Soil gas/surface flux | Surface seepage | • Preinjection surveys in 2004<br>• Repeat survey in 2009 |
| 3D-4D seismic | Plume migration | • Initial survey in 1997<br>• High-resolution survey acquired in mid-2009. Provides feasibility evaluation for 4D |
| Deep-observation wells | Plume migration | • Not planned at present due to cost |
| Microseismic | Cap rock integrity | • Test well drilled mid-2009 above KB-502 injector<br>• Depth 500 m, 1500 m above injection zone, 50 geophones array (10 three-component)<br>• Recording ongoing |
| Electromagnetic surface and wellbore | Plume migration | • Not useful at Krechba due to subsurface architecture and logistics<br>• Wells too widely spaced |
| Gravity | Plume migration | • Modeling suggests surface response negligible<br>• May be tested in 2011<br>• Borehole gravity possible if suitable access available |
| VSP | Cap rock integrity<br>Plume migration<br>Fracture evaluation | • Modeling results inconclusive<br>• Decision pending 3D VSP into microseismic array |
| Shallow aquifer wells | Contamination of potable aquifer<br>Cap rock breach | • Seven shallow aquifer wells drilled<br>• Sampling twice per year |
| Microbiology | Surface seepage | • First samples collected in late 2009 |
| Eddy covariance flux towers and LIDARs | Surface seepage | • Reviewed, but weather conditions and potential equipment theft ruled this out<br>• Reviewing potential for deployment in 2011 |
| InSAR monitoring | Plume migration<br>Cap rock integrity<br>Pressure development | • Used extensively, contributions and commissioned work from several providers<br>• Images captured every 28 days |
| Tiltmeters/GPS | Plume migration<br>Cap rock integrity<br>Pressure development | • To calibrate InSAR deformations<br>• 70 tiltmeters deployed around KB-501 in late 2009 |

Fig. 24. The summarized monitoring technologies and status In Salah, Algeria (Aleksandra et al., 2010; Mathieson et al., 2010).

continuous bottom-hole pressure; reservoir surveillance wells by saturation logs and pressure changes above well perforations; surface seismic monitoring over plume area and time lapse 3D; and surface monitoring by soil gas flux sampling grids and seepage points (Aleksandra et al., 2010; Flett et al., 2009). A integrated reservoir surveillance was planned as shown in Figure 26 (Aleksandra et al., 2010; Flett et al., 2009).

### • Weyburn

Weyburn $CO_2$ project is a commercial scale site with 2.7 Mt per year injection rate. The Weyburn Oilfield was stimulated by water injection in 1996 after 20 years production. For $CO_2$ storage, there are two projects. One is for $CO_2$ enhanced oil recovery managed by EnCana; another is International Energy Agency Greenhouse Gas Weyburn-Midale $CO_2$ Monitoring and Storage project run by Petroleum Technology Research Center (Aleksandra et al., 2010; Hutcheon et al., 2003; Stalker et al., 2009). The main technologies used to monitor in the first

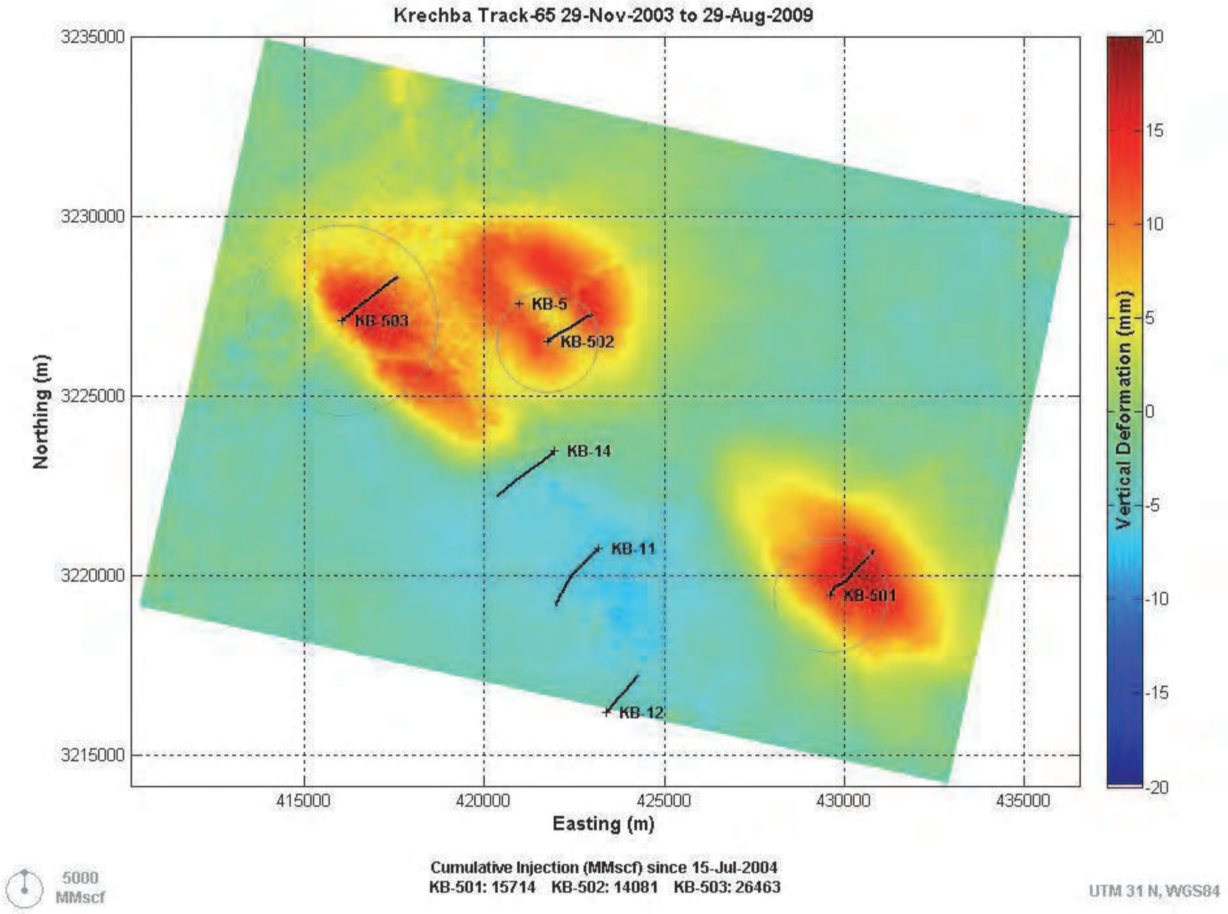


Fig. 25. An example of ground deformation monitoring In Salah, Algeria (Wildenborg, 2011).

phase of the Weyburn are seismic images and geochemical methods from $CO_2$ injection in September 2000. As an example, results of geochemical monitoring were reported in Figure 27 (Hutcheon et al., 2003; Stalker et al., 2009). In this figure, (a) and (b) indicate the changes of $\delta^{13}CHCO_3$, (c) and (d) show the variations of calcium, and (e) and (f) are the increasing of total alkalinity within 289 and 980 days from the beginning of injection.

- **Frio**

The storage site of Frio is located in the South Liberty oilfield, southeast of Houston. This project started from 2002 for the pilot demonstration of $CO_2$ storage with funding by the National Energy Technology Laboratory of US DOE. The injection rate of the project was designed as 160 tonnes per day for fating to the brine-bearing sandstone-shale system. Regarding the $CO_2$ monitoring, there is a list summarize the techniques being used in Figure 28 (Aleksandra et al., 2010; Doughty et al., 2008; Myer et al., 2003).

## 4. Gaps in knowledge of monitoring technologies

In the past decade, $CO_2$ monitoring technologies have been making significant progress in subsurface and at surface, based on the geophysical equipments, geochemical experiments, and modeling methods. Particularly, based on the Special Report on $CO_2$ Capture and Storage by the IPCC (Metz, Davidson, Coninck, Loos & Meyer, 2005), the knowledge gaps

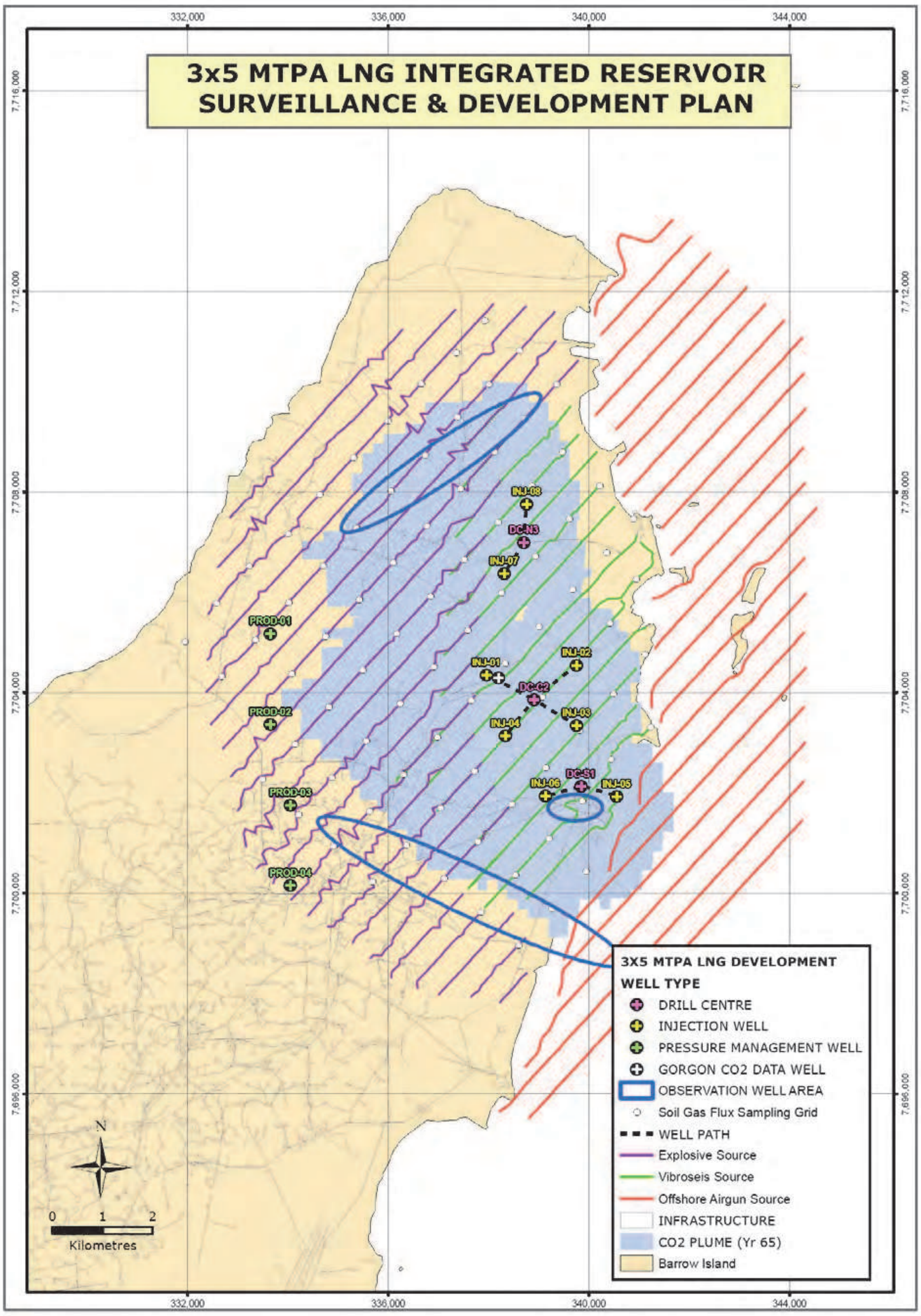


Fig. 26. An integrated reservoir surveillance design for the Gorgon project in Australia (Wildenborg, 2011).

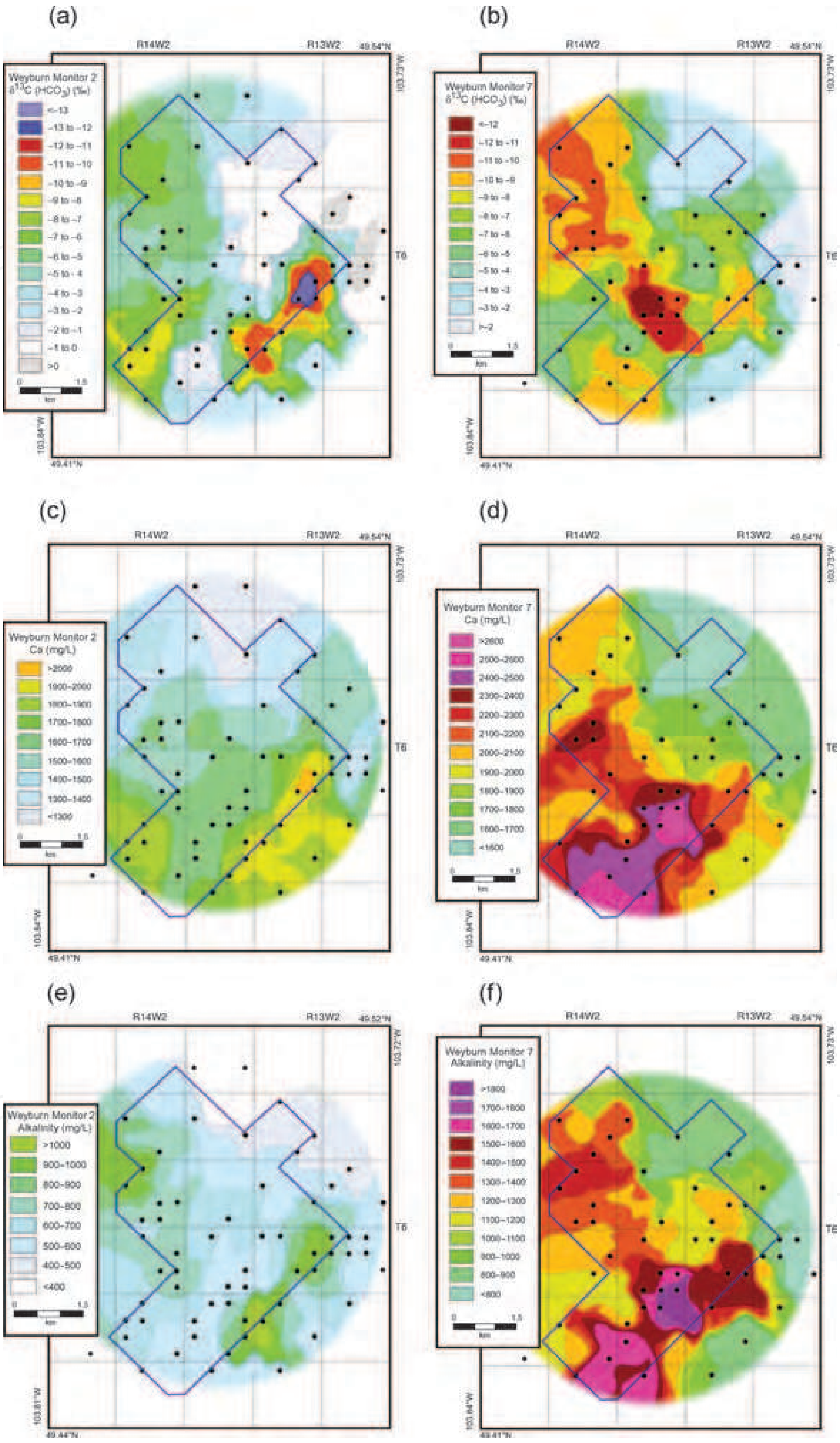
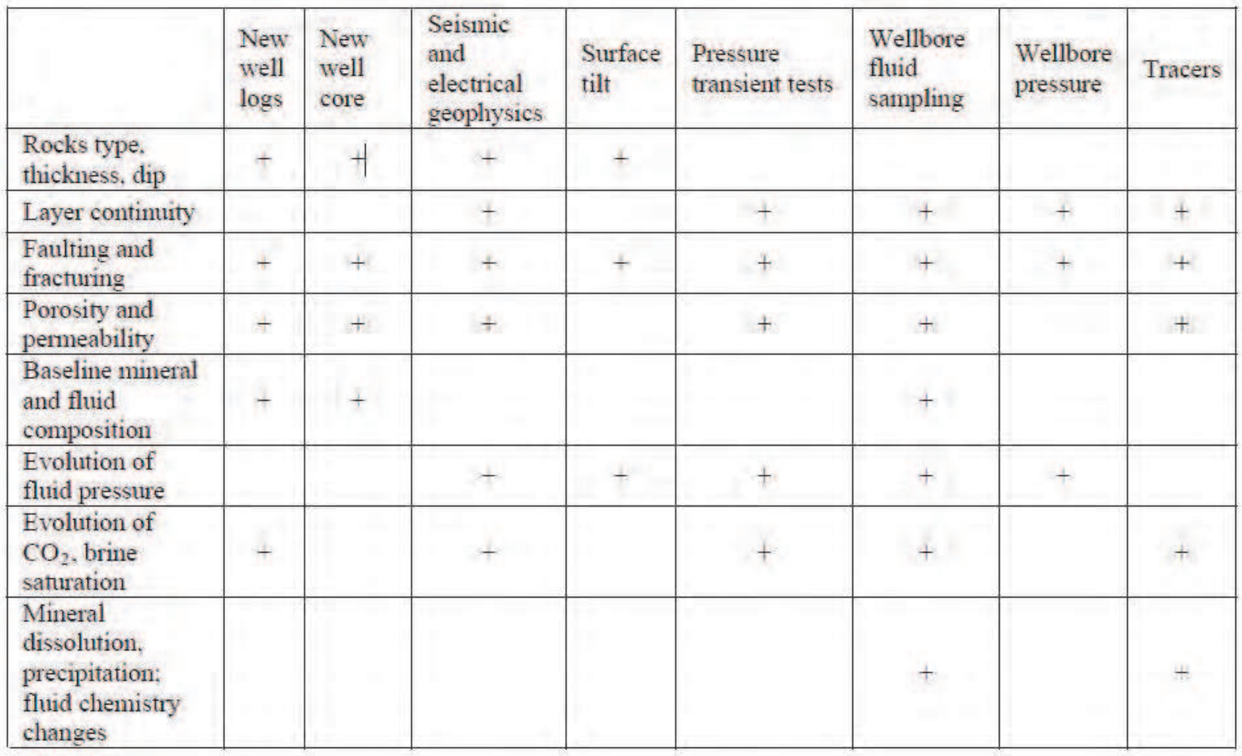


Fig. 27. Geochemical monitoring results at Weyburn, Canada (Hutcheon et al., 2003; Stalker et al., 2009).



| | New well logs | New well core | Seismic and electrical geophysics | Surface tilt | Pressure transient tests | Wellbore fluid sampling | Wellbore pressure | Tracers |
|---|---|---|---|---|---|---|---|---|
| Rocks type, thickness, dip | + | + | + | + | | | | |
| Layer continuity | | | + | | + | + | + | + |
| Faulting and fracturing | + | + | + | + | + | + | + | + |
| Porosity and permeability | + | + | + | | + | + | | + |
| Baseline mineral and fluid composition | + | + | | | | + | | |
| Evolution of fluid pressure | | | + | + | + | + | + | |
| Evolution of $CO_2$, brine saturation | + | | + | | + | + | | + |
| Mineral dissolution, precipitation; fluid chemistry changes | | | | | | + | | + |

Fig. 28. Monitoring technologies used in the Frio $CO_2$ storage (Aleksandra et al., 2010; Myer et al., 2003).

of monitoring technologies have been addressed frequently (Aleksandra et al., 2010; Michael et al., 2009; $CO_2$STORE, 2007; IEA, 2007; 2009; Michael et al., 2009; 2010; NETL, 2009; Zahid et al., 2011).All of the technologies reviewed in this chapter show abilities (or potential abilities) in field application with pre-demonstration. However, though some improvements were suggested to fill some of knowledge gaps, the main problems of developing practical and cost-effective technologies for field-scale monitoring application are still open for more explorations (Michael et al., 2009; IEA, 2009; Michael et al., 2009; 2010; NETL, 2009). The main aspects of the technologies are summarized as below (Benson & Gasperkova, 2004):

- **Seismic Technologies**

Seismic technologies, as a very good and popular monitoring set, have been applied to several worldwide $CO_2$ storage projets because of the high spatial resolution and high sensitivity on small $CO_2$ amounts in the subsurface. However, seismic techniques cannot reflect the $CO_2$ information where the seismic source, such as impedance cannot distinguish the variation like the low porosity geological media, consolidated or cemented sandstone, rigid carbonates etc as discussed in Figure 3. In particular, when the small amount of $CO_2$ near the gaseous phase, it is hard to monitor such $CO_2$ migrations by seismic techniques. On the other hand, the interpretation of seismic data in the pore space needs to be much quantized, which would help to figure out the $CO_2$ behaviors in the formation accurately.

- **Electromagnitic Technologies**

Electromagnitic technologies show the potential ability on monitoring of $CO_2$. However, the accuracy of hardware needs to be improved, especially on the distinguish of mixture fluids such as $CO_2$ and water. On the other hand, because electromagnitic technologies are relatively new, the demonstrations of the technologies are expected to show the real capacity of the large-scale of $CO_2$ monitoring and develop experience for the applications.

### • Gravity Technologies

Gravity monitoring technologies are better options for dissolved $CO_2$ that are used in the Sleipner, Norway, and Schrader Bluff, Alaska. However, the technologies still need more research for the mature field application. First of all, the instrument for the gravity measurements need to be improved with avoiding noise, measuring gravity change accurately, and cost competence. Second, if using the potential ability of gravity technologies to estimate the saturation changes, the quantitative methods need to be more efficient based on the inversion algorithms.

### • Surface/Near-Surface Fluxes Technologies

Most of the current technologies for surface/near-surface $CO_2$ monitoring with supposing of the known leakage location so that the ground-based or airplane based technologies can be successfully used to detect the $CO_2$ compositions. However, the monitoring of $CO_2$ footprint probably hundreds of square kilometers, according to the suggestion by Benson & Gasperkova (2004). It means that the monitoring locations and quantifications are very tough by local technologies. Moreover, the background $CO_2$ varies over the monitoring location and time. So, the better methods for surface/near-surface monitoring may more depend on the development of the technologies of remote sensing and satellite-based observing (Benson & Gasperkova, 2004).

### • Geochemical and Tracers Monitoring Technologies

The main works of the geochemical and tracers monitoring technologies lie on the sensitivity of tests and regulations management. Moreover, the geochemical reactions between the well (including abandoned well) and surrounds need more work on figuring out the mechanisms. These reactions include what may happen among annulus cement, plug cement, casing wall over the pH value, which particularly depends on the compositions of the injected $CO_2$.

Moreover, some more specific techniques applied in the above technologies need to be more addressed.

- Sensors used in the borehole for onshore and offshore monitoring technologies need to consider the temperature and pressure changes over the depth of the well. Specifically, the $CO_2$ sensor and pH sensor strongly require such considerations because of their sensitivity.

- The fingerprint recognitions of tracers, including gas tracers and hydrogeological tracers, need more works on figuring out the leakage of $CO_2$.

- The modeling of $CO_2$ monitoring requires an integrated system, which couples various physical phenomena, such as geochemical reactions, geomechanical behaviors, and geothermal effects into the dynamic model to comprehensively and accurately evaluate the sink-seal system. On the other hand, the related data sets for this integrated system are far away to meet the requirements of the modeling. More field measurements and laboratory tests definitely improve the reliability of the model predictions.

As stated, the $CO_2$ monitoring is a integrated process which start from the beginning of the geological exploration, site characteristics, and storage formation(s) identifications lasting to the phases of $CO_2$ injection and post-injection. Generally, the designs of $CO_2$ monitoring and choices of technologies need to be considered with the integrated process. As a general guideline, IEAGHG released a monitoring selection tool based on the potential technologies with considering storage options and periods (IEAGHG, 2010). Moreover, Myer (2000) suggested that the strategy for development of monitoring technologies with a focus on the $CO_2$ monitoring is a three step approach, involving (1) numerical simulation and laboratory experiments to assess technique sensitivities, (2) field testing at different scales in different formations, and (3) analysis and integration of complimentary data. This iterative approach will permit selection of the most cost-effective combination of techniques for the particular formation and sequestration activity being considered by Myer (2000). However, the more details on systemic strategies and optimizations of $CO_2$ monitoring are still open for further research and field investigations, especially location-based strategy and optimization designs. The suggestion for such designs would be based on the knowledge databases of the world and regulations of the location with cost-effective consideration.

## 5. Conclusions

In this study, the most recent $CO_2$ monitoring technologies were reviewed with their applications in fields as examples. The cost of each $CO_2$ monitoring technology was compared based on the previous research. According to the $CO_2$ monitoring technologies being used, several $CO_2$ storage sites in worldwide were analyzed. All of reviews shown that the technologies for $CO_2$ monitoring have been enhanced more by compared in past decade. Though some of the technologies are still in the beginning stage, they indicate the positive potential of applications in the near-future. Moreover, the general gap of knowledge related to the technologies were partly resealed. With the suggestions for the gap of knowledge, these technologies will play more important roles in $CO_2$ monitoring by a accurate and cost-effective way.

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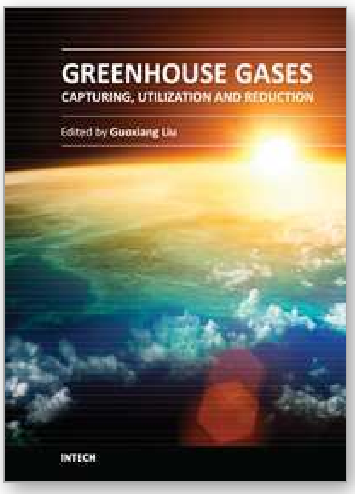

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Understanding greenhouse gas capture, utilization, reduction, and storage is essential for solving issues such as global warming and climate change that result from greenhouse gas. Taking advantage of the authors' experience in greenhouse gases, this book discusses an overview of recently developed techniques, methods, and strategies: - Novel techniques and methods on greenhouse gas capture by physical adsorption and separation, chemical structural reconstruction, and biological utilization. - Systemic discussions on greenhouse gas reduction by policy conduction, mitigation strategies, and alternative energy sources. - A comprehensive review of geological storage monitoring technologies.

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**InTech Europe**
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Phone: +86-21-62489820
Fax: +86-21-62489821