APPLIED GEOPHYSICS, Vol.13, No.2 (June 2016), P. 288-306, 17 Figures.
DOI:10.1007/s11770-016-0553-1

Geophysical monitoring technology for CO_2 sequestration*

Ma Jin-Feng♦[1], Li Lin[1], Wang Hao-Fan[1], Tan Ming-You[2], Cui Shi-Ling[2], Zhang Yun-Yin[2], Qu Zhi-Peng[2], Jia Ling-Yun[1], and Zhang Shu-Hai[3]

Abstract: Geophysical techniques play key roles in the measuring, monitoring, and verifying the safety of CO_2 sequestration and in identifying the efficiency of CO_2-enhanced oil recovery. Although geophysical monitoring techniques for CO_2 sequestration have grown out of conventional oil and gas geophysical exploration techniques, it takes a long time to conduct geophysical monitoring, and there are many barriers and challenges. In this paper, with the initial objective of performing CO_2 sequestration, we studied the geophysical tasks associated with evaluating geological storage sites and monitoring CO_2 sequestration. Based on our review of the scope of geophysical monitoring techniques and our experience in domestic and international carbon capture and sequestration projects, we analyzed the inherent difficulties and our experiences in geophysical monitoring techniques, especially, with respect to 4D seismic acquisition, processing, and interpretation.
Keywords: Carbon capture and storage, geophysical monitoring, 4D seismic monitoring, CO_2 saturation, reservoir pressure

Introduction

Responding to the devastating effects of climate change is one of the greatest challenges facing the world today because climate change poses the greatest threat to the future sustainability of humanity (IPCC, 2014). Overwhelming scientific evidence has proved that human activities since the industrial revolution, in particular, those of the developed countries, have produced great amounts of cumulative CO_2 emissions by the use of fossil fuels, which has resulted in a significant increase in the atmospheric concentrations of greenhouse gases (Chu, 2009; Sun, 2006). Higher temperatures and extreme weather events have serious impacts on global natural ecosystems and a particularly significant impact on food production, which threatens human survival and sustainable development.

Carbon capture and sequestration (CCS) or carbon capture, utilization and sequestration (CCUS) is a technology that can capture CO_2 from coal-fired power plants or other large CO_2 emission sources and store it safely underground. According to estimates from the International Energy Agency (IEA, 2013),

Manuscript received by the Editor November 5, 2015; revised manuscript received March 6, 2016.
*This work was supported by National 863 Program Grant 2012AA050103 and Grant 2011KTCQ03-09.
1. State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China.
2. SINOPEC Shengli Geophysical Research Institute, Dongying 257022, China.
3. SINOPEC Zhongyuan Geophysical Research Institute, Puyang 457001, China.
♦Corresponding author: Ma Jin-Feng (Email: jfma@nwu.edu.cn)

CCS technology could reduce one-sixth of the global carbon emissions by 2050. It is currently recognized internationally as the most efficient way to quickly reduce the greenhouse effect (Bikle, 2009). Although CCS technology and other technologies such as renewable energy, nuclear energy, or energy-efficient technologies are key technologies for dealing with climate change, CCS technology is the most direct and critical technology for reducing carbon emissions from power generation, steel, metallurgy, glass, ceramics, cement, and chemical industries based on fossil fuels.

Since the success of CCS operations in the Weyburn oil field in Canada, the Sleipner gas field in Norway, and the In Salah saline aquifer storage in Algeria (Service, 2009), more international CCS projects are entering into construction and operation phases. In October 2014, the world's first one-million-scale post-combustion CO_2 capture CCS project became operational at SaskPower's Boundary Dam power station in Saskatchewan, Canada (Reiner, 2016). This is regarded as a global milestone for "clean coal" technology. At the end of 2014, there were 22 large-scale global integrated CCS or CCUS projects either in operation or under construction (GCCSI, 2014). China currently has several small development projects for CO_2 capture, CO_2-enhanced oil recovery (EOR), and sequestration. Four of these projects are integrated CCS projects, including CO_2 capture, transport, and storage. They include the CO_2-EOR project in the Jilin oilfield, the Ordos Shenhua saline aquifer CO_2 storage projects, the Jingbian CCS Project of the Shaanxi Yanchang Petroleum Group, and the Shengli oilfield post-combustion carbon capture CCUS Project. Of these four integrated CCS projects, the Jingbian and Shengli CCS projects have been listed as low-carbon promotion technologies by China's National Development and Reform Commission (NDRC, 2014, 2015) since 2014. In June 2015, the Jingbian CCS Project became China's first CCS project recognized by the Carbon Sequestration Leadership Forum (CSLF) (CSLF, 2015). On September 25, 2015, the Jingbian CCS Project of the Shaanxi Yanchang Petroleum Group was listed in the China–US Joint Presidential Statement on Climate Change. It is also China's first large-scale commercial CCUS project on which China and the U.S. will cooperate (Chinese Government, 2015).

CCS projects have the potential to grow into a big market and open up new areas for the application of geophysical technologies. Geophysical monitoring is a key technology for identifying CO_2 geological storage sites, monitoring CO_2 migration, and evaluating the safety of geological storage underground (Wills et al, 2009; Lawton, 2010). In this paper, we focus on the challenges and opportunities of geophysical technology for CO_2 sequestration.

Feasibility of CO_2 sequestration

The CO_2 sequestration process is equivalent to the inverse of the oil and gas development process, in which captured CO_2 is injected into underground geological traps for safe and permanent storage. At present, the CO_2 sequestration method internationally recognized as most cost-effective is to capture CO_2 from large-scale emission sources and inject it into depleted oil and gas fields or into those in the late development stage. These oil fields have structural and stratigraphic traps that have stored oil and gas for millions of years without leakage, and which are ideal safe geological storage places for CO_2. In addition, depleted oil fields have accumulated a large number of drilling sites, core samples, geological study results, geophysical measurements, formation and production test results, and other information regarding the oil exploration and development process. Their use can save considerable expense with respect to the selection and baseline safety monitoring of CO_2 geological storage sites. More importantly, the use of CO_2-EOR can obtain 10% more than recovery by water injection. This additional revenue from CO_2-EOR can compensate for the cost of the entire CCUS project. If we consider the environmental benefits, the use of CO_2 flooding not only saves water but also reduces the waste-water discharge from water or chemical flooding.

Although an oil and gas reservoir is the best place to carry out CCUS, its capacity for CO_2 sequestration is much smaller than that of a deep saline aquifer. The potential capacity of saline aquifers for CO_2 sequestration is huge. How to reduce the cost of CO_2 storage in saline aquifers and then utilize the brine is also an important challenge for international research and development.

The conditions and requirements for CO_2 sequestration include:

(1) Storage site selection, determination of the lithology, structure, traps, capacity, permeability, saturation, temperature, pressure, and other reservoir parameters, and more accurate analyses of the rock fabric, porosity, and micro-cracks prior to CO_2 injection;

(2) An understanding of the reservoir geometry, the thickness and extension of the seal layers, and the geometric features and characteristics of its faults and

fractures;

(3) An understanding of the geological structure of saline aquifers near major CO_2 injection reservoirs and lithology information about their caprocks;

(4) Determination of the distribution of residual oil and CO_2-EOR efficiency;

(5) Verification of the integrity of the caprock and well bore, and detection of any CO_2 leakage and migration underground;

(6) Verification of the stability of the CO_2 plume and its prevention from spreading by secondary seals if CO_2 breaks through the first caprock; confirmation of the reservoir pressure and the actual CO_2 storage capacity of the reservoir;

(7) Forecast of surface deformation and the rock mechanics of overlying layers;

(8) An understanding of the mechanisms of long-term CO_2 geological storage and geochemical reactions during storage (Matter and Kelemen, 2009);

(9) Leakage risk assessment;

(10) The development and application of near-surface and atmospheric rapid monitoring techniques and an understanding of the environmental effects of CO_2 leakage with respect to the underground geological structure.

The most important scientific questions are how to improve the efficiency of CO_2-EOR during CO_2 sequestration and how to ensure that CO_2 will be safely retained for at least 200 to 1000 years. Geophysical techniques will play a vital role, and the biggest challenges in the development of these techniques include: how to measure and monitor CO_2-EOR efficiency; how to verify the safety of CO_2 sequestration within reservoirs thousands of meters deep; how to confirm that the amount of CO_2 stored in a deep reservoir is equal to that of the injected CO_2; and how to detect potential fast and slow leakage points.

Geophysical monitoring techniques in CO_2 sequestration

Current geophysical monitoring techniques for CO_2 sequestration include:

1) Four-dimensional (4D) seismic technology, including 4D and three-component seismic techniques (4D3C), 4D and three-component vertical seismic profile technology (4D3CVSP), 4D and nine–component seismic techniques (4D9C) (White, 2012, 2013; Davis et al., 2003), crosswell seismic tomography (Onishi et al., 2009; Spetzler et al., 2008; Zhang et al., 2015), and passive seismic monitoring (Verdon et al., 2010; Ugalde et al., 2013);

2) Borehole geophysical monitoring techniques (Xue et al, 2006) including time lapse logging techniques, multi-level borehole temperature and pressure monitoring techniques;

3) Rock physics experiments (Brown, 2002; Xue and Lei, 2006; Martínez and Schmitt, 2013), i.e., experiments that simulate reservoir temperature, injection pressure, and other parameters under CO_2 flooding conditions;

4) Resistivity methods (Kiessling et al., 2010; Bergmann et al., 2012), including surface and borehole monitoring techniques;

5) Gravity monitoring (Alnes et al., 2011; Gasperikova and Hoversten, 2008);

6) Remote sensing (Verkerke et al., 2014) and surface deformation monitoring (He et al., 2014; Samsonov et al., 2015).

Geophysical monitoring is performed throughout every stage of CO_2 sequestration, i.e., prior to CO_2 injection (baseline), during injection (monitoring) and after closure (post-closure monitoring). After the closure of a CO_2 sequestration project, the security and safety of the CO_2 storage must be monitored over the long term (Ma and Zhang, 2010; Hao and Yang, 2012). During this stage, seismic monitoring is the most effective technique for subsurface monitoring.

Seismic monitoring for CO_2 sequestration is a long-term process that mainly employs 4D (also known as time-lapse) seismic monitoring techniques. The 4D seismic differences of amplitude and small travel time within the reservoir are obtained by comparing seismic monitoring and baseline data or different monitoring datasets, and are used to estimate the vertical and horizontal distribution of the CO_2 plume. 4D seismic monitoring for CO_2 sequestration has been successfully applied in Canada (White, 2009), Norway (Chadwick et al., 2010), Australia (Urosevic et al., 2010; Pevzner et al., 2011), the European Union (Kiessling et al., 2010; Ivanova et al., 2012), and the United States (Finley, 2014). Figure 1 shows amplitude differences from 4D seismic monitoring data in Canada's Weyburn field. Nearly all global CO_2 sequestration projects have implemented either baseline seismic monitoring or seismic surveys to evaluate storage sites.

Compared with surface 4D seismic monitoring techniques, it is more difficult to implement vertical seismic profiling (VSP) and cross-borehole seismic tomography during CO_2 injection and especially after site closure. For example, existing VSP, micro-seismic monitoring, and downhole monitoring techniques are carried out at monitoring wells at small test areas. It is difficult to put seismic sources and receivers in both CO_2 injection wells and producing wells. If CO_2 injection is stopped or the production of oil is stopped to monitor seismic data, the bottomhole pressures of the injection and production wells will differ from those in active operation. There could be a risk of a large amount of CO_2 being leaked from the CO_2 injection, production, or monitoring wells. Also, if CO_2 injection is stopped, water could gush up from the borehole, possibly preventing future injection of CO_2 such that the operation would have to be permanently shut down.

Of the current CO_2 sequestration projects in the world,

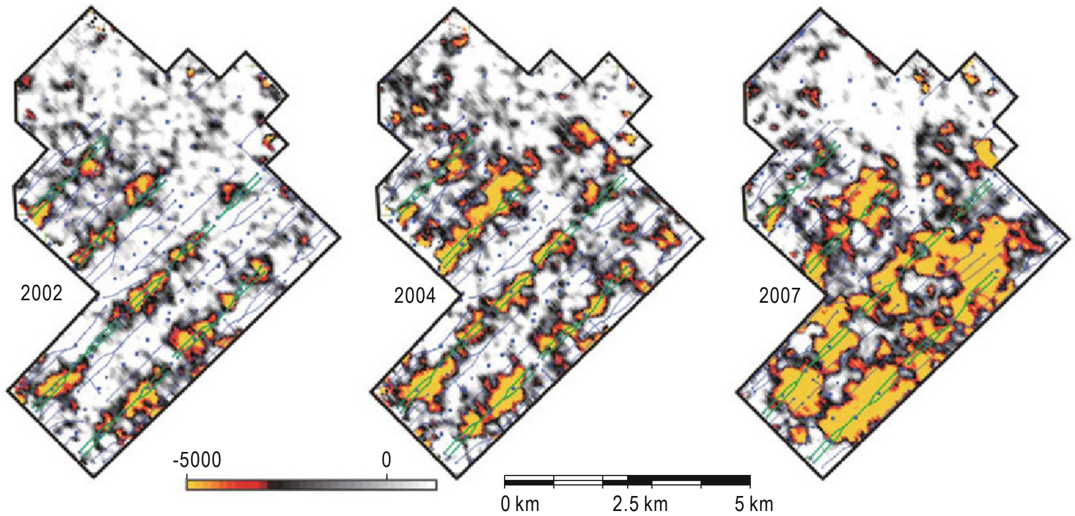

Fig.1 Differences of seismic amplitude at the top of the Marly unit of the Weyburn field, Canada. The labels 2002, 2004, and 2007 indicate the year in which the 3D seismic monitoring data was acquired: 2.80 million tons of CO_2 were injected in 2002, 3.70 million tons of CO_2 were injected in 2004, and 7.40 million tons of CO_2 were injected in 2007, minus the baseline 3D seismic data acquired in 1999. The black lines represent horizontal production wells and green lines represent horizontal CO_2 injection wells (White, 2009). The yellow areas represent CO_2 distribution areas.

the most comprehensive seismic monitoring techniques have been applied in Canada's Weyburn field (White, 2013), including five 3D3C seismic surveys, three 3D VSP surveys, three 3D9C surveys, and five passive seismic surveys before and during CO_2 injection. Before injecting CO_2, a new borehole, Well 4-23 (Figure 2), was drilled and logged at the edge of the 3D seismic survey area (Ma and Morozov, 2010), and integrated well logs were measured in this well, including fast and slow shear wave velocities. Later, Well 4-23 was converted to a water-injection well. Unfortunately, this new well is not a core drill well. Core samples have been acquired from two other core boreholes (Figure 2), and a rock physics experiment was conducted at the Colorado School of Mines (Brown, 2002).

In CO_2 sequestration projects being conducted in depleted oil fields, there is often a shortage of drill cores, as well as of dipole sonic logs. Alternatively, there are drill core samples, but no dipole sonic logs. These shortcomings in the data affect the ability to correspond core samples to well logs and influences the accuracy of

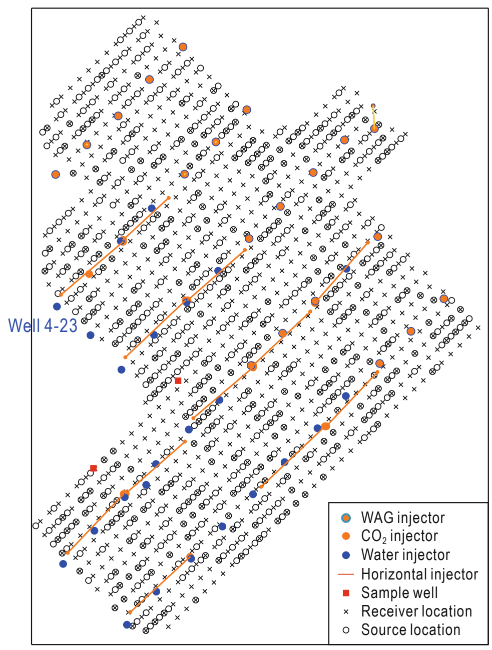

Fig.2 4D seismic surveys (Phase 1A) with well locations in the Weyburn field. WAG indicates water-alternating gas (CO_2).

subsequent fluid substitution calculations.

In order to avoid seasonal surface velocity changes, 4D seismic monitoring in the Weyburn field is on a fixed annual schedule from the end of November to early December. Surface velocity changes could cause differences between repeated seismic surveys. In actual vintage seismic acquisitions, due to the use of dynamite sources and the replanting of receivers, it is very difficult to achieve identical repeatable geometries. That is, it is difficult to maintain consistency in the source and receiver locations in repeated 3D seismic surveys (Ma et al., 2009). Figures 3 and 4 show the differences in the shot and receiver locations between the baseline and monitoring seismic surveys in the Weyburn field.

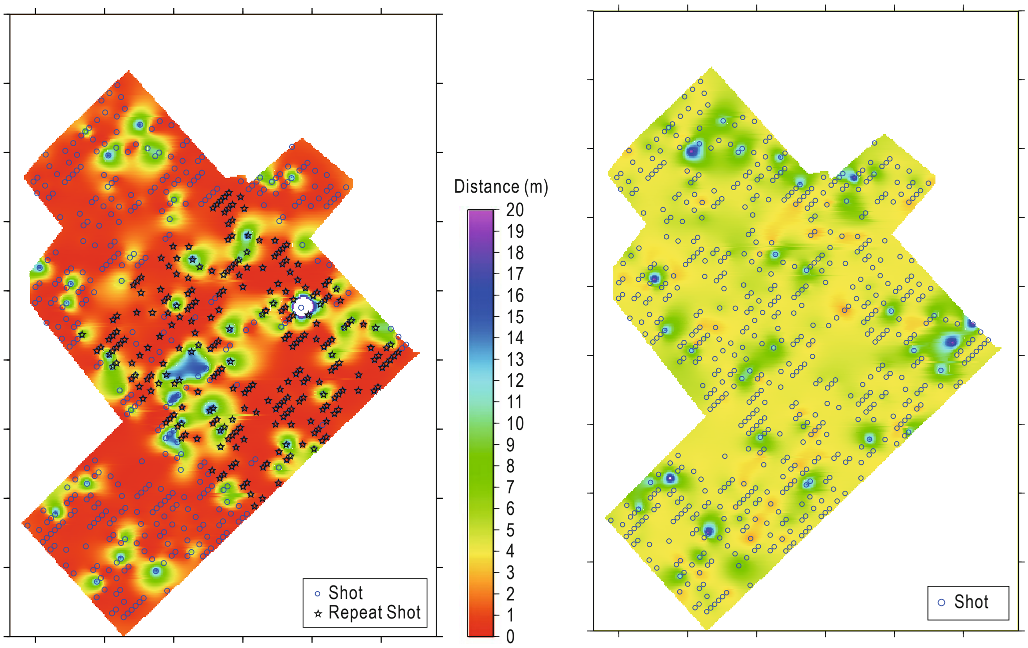

Fig.3 Differences in the source coordinates between baseline and monitoring seismic surveys (Ma et al., 2009). Left: 2001 monitoring data minus the 1999 baseline source coordinates; right: 2002 monitoring data minus the 1999 baseline source coordinates.

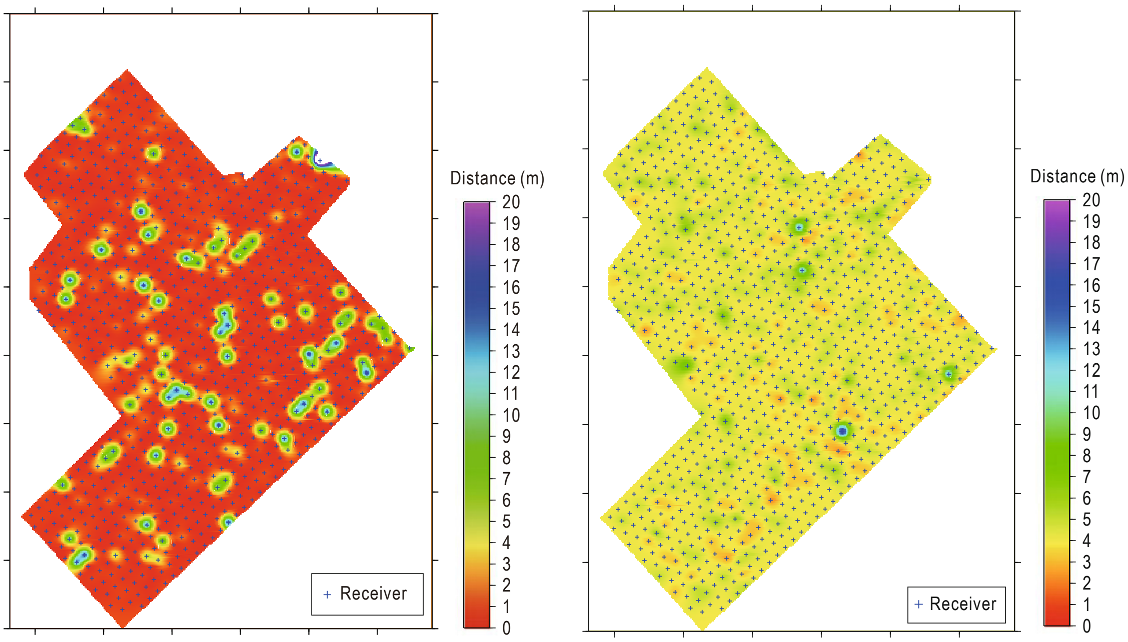

Fig.4 Differences in receiver coordinates between the baseline and monitoring seismic surveys (Ma et al., 2009). Left: 2001 monitoring data minus the 1999 baseline receiver coordinates; right: 2002 monitoring data minus the 1999 baseline receiver coordinates.

Nevertheless, attempts have been made to maintain consistency in the source and receiver locations of the monitoring seismic surveys in the Weyburn field with those of the baseline seismic surveys. Table 1 lists the seismic acquisition parameters. The first 3D seismic monitoring data were acquired in the year 2001, after one million tons of CO_2 had been injected and stored underground (Table 1). Although the 3D seismic geometry of the 2001 monitoring data differs from that of the 1999 baseline data, the amplitude and travel-time differences between the monitoring and baseline data were obtained (Li, 2003), which gave researchers some confidence and laid the foundation for conducting subsequent 3D seismic monitoring. Based on the lessons learned from the changing geometry in the year 2001, the monitoring seismic geometry for the year 2002 were changed to be consistent with the 1999 baseline seismic geometry (Table 1).

Table1 4D seismic acquisition parameters in the Weyburn field (Ma et al., 2009)

Parameters\Year	Baseline (1999)	Monitor (2001)	Monitor (2002)
Shot number	630	882	630
Receiver station	986	986	986
Sample rate (ms)	2	2	1
Maximum offset	2152.87	3445.84	2105.627
Maximum fold	77	132	78
Source type	Dynamite, 1 kg, 12 m	Dynamite, 1 kg, 12 m	Dynamite, 1 kg, 12 m
Receiver type	Mitcham, 3C Frequency 10 Hz Damping 70%	OYO, 3C Frequency 10 Hz Damping 1%	OYO, 3C Frequency 10 Hz Damping 0.7%
Source interval (m)	160	160	160
Receiver interval (m)	160	160	160
Patch	19 lines × 39 stations	19 lines × 39 stations	19 lines × 39 stations

The 4D seismic monitoring used for CO_2 sequestration (Calvert, 2005; Johnston, 2013) differs from that used to monitor flooding of water, heavy oil, steam assisted gravity drainage (SAGD), and steam flood. The elastic properties of supercritical CO_2 under reservoir temperature and pressure are similar to those of gas. When CO_2 is injected into a reservoir, the P-wave velocity of the reservoir decreases rapidly so that it is easy to measure variations of the seismic amplitude and travel-time delay during CO_2 flooding. Taking the Weyburn field carbonate reservoir as an example, we calculated that the P-wave velocity would change by 10% from that of the fluid substitution model during CO_2 flooding. In carbonate rock physics experiments, Wang et al. (1998) also found that P-wave velocity could drop an average of 9% for high-porosity core samples and drop an average of 4% for low-porosity core samples.

In their sandstone rock physics experiment in the Nagaoka Pilot Project, Xue and Li (2006) found that by increasing CO_2 saturation, P-wave velocity may be reduced by more than 10% (Figure 5). However, when CO_2 saturation surpasses 20%, the P-wave velocity of sandstone sample no longer declines. As a result, it then becomes a technical problem of how to invert CO_2 saturation by seismic inversion when CO_2 saturation has surpassed 20%.

In the Nagaoka Pilot Project, Kim et al. (2011) confirmed that resistivity changes significantly with CO_2 saturation, as shown in Figure 5. As a consequence, monitoring resistivity could be an effective way to identify CO_2 saturation. However, insufficient resolution of resistivity imaging could pose a problem. Also, when CO_2 is injected into a reservoir, it dissolves in water and

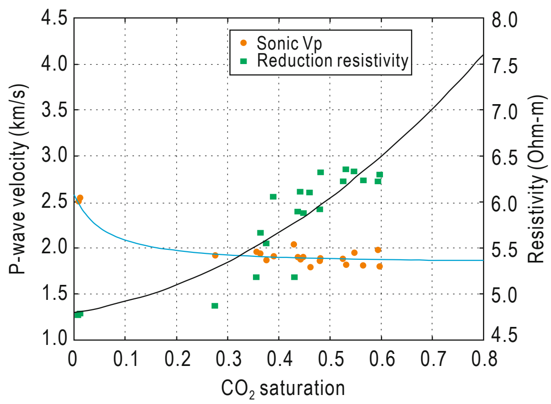

Fig.5 P-wave velocity and resistivity varying with CO_2 sequestration (Kim et al., 2011)

forms carbonic acid. Carbonic acid dissolves minerals, which causes salinity to increase and a decrease in the resistivity of the formation water. As such, if the actual monitored reservoir resistivity is affected by the CO_2 and formation water resistivity, it becomes difficult to obtain an accurate measurement of CO_2 saturation.

The change in pore pressure or confining pressure (overburden pressure minus pore pressure) during CO_2 injection is a main factor affecting the elastic parameters of a reservoir as well (Figure 6). The impact of pressure on the elastic parameters, such as P-wave velocity, could be greater than that of CO_2 saturation, especially in the late development stages of an oil field and in the early stages of CO_2 injection. Since shear wave velocity is not sensitive to CO_2 saturation, pressure change is the main factor influencing shear wave velocity. For example, in the Jingbian CCS Project of the Shaanxi Yanchang Petroleum Group, when CO_2 injection began in September, 2012, the reservoir pressure had already dropped from the original 12 MPa to 2−3 MPa. In the Gao 89 CO_2 injection area of the SINOPEC Shengli oil field, the reservoir pressures dropped from 42.6 MPa to 28.1−32.2 MPa when CO_2 injection began. In Canada's Weyburn field, the original reservoir pressure was 15 MPa, and when CO_2 injection began, the bottomhole pressure of the injection well was 23 MPa, and the pressure of the producing well was 8 MPa (Ma and Morozov, 2010). In addition, reservoir temperature, brine salinity, gas-to-oil ratio, and the crude oil API also affects the elastic parameters of the reservoir.

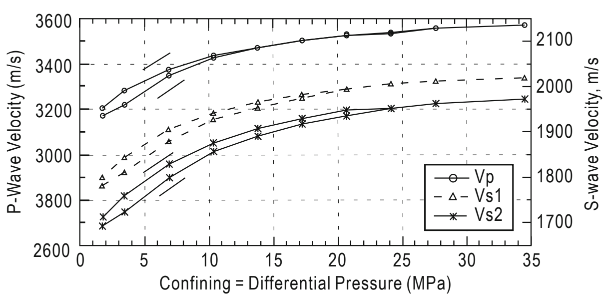

Fig.6 Changes in the P-wave and shear wave velocities with the confining pressure of a dolomite dry sample in the Marly unit of the Weyburn field (Brown, 2002).

Other geophysical methods are generally used in conjunction with 4D seismic monitoring to obtain reservoir parameters at different stages of CO_2 injection. These geophysical methods should be conducted at the same time as the seismic acquisitions. These data can then be used to calibrate the 4D seismic data. For example, time-lapse well logging must be carried out in order to accurately calibrate the baseline and monitoring seismic data, including all the well logs measured prior to CO_2 injection or in open hole wells. After CO_2 injection, the temperature, oil saturation, pressure, resistivity, gas-to-oil ratio, and brine salinity will be changed. Even the porosity could be changed by fracturing, acidification, and carbonic acid dissolution. Therefore, time-lapse well logging is necessary to obtain accurate reservoir parameters. However, due to the cementing and casing of the wells, time-lapse well logging will be influenced by the steel casing pipe, making it difficult and expensive to perform accurately. At present, of all the CO_2 sequestration projects in the world, time-lapse well logging has been conducted only at the Nagaoka Pilot Project (Xue et al., 2006), and neutron, induction, and sonic logs (Nakajima and Xue, 2013) were measured only several to 40 times. For this reason, the use of Gassmann's theory to calculate fluid-substitution well logs remains the primary method of estimating the elastic parameter curves of a reservoir at different stages of CO_2 sequestration.

When time-lapse well logging cannot be carried out, rock physics experiments must be performed to establish a relationship between reservoir pressure and the elastic parameters (Brown, 2002). Then, the well logs can be corrected or fitted to reservoir conditions that are consistent with the seismic data acquisition time, i.e., reservoir parameters such as temperature, injection pressure, and oil saturation, so that the well logs match the 4D seismic data. Further, reservoir models could be developed based on the corrected well logs to interpret 4D seismic data and perform seismic inversion (Mezghani et al., 2004; Roggero et al., 2007).

Passive seismic monitoring can be used to monitor possible CO_2 breakthrough locations caused by high injection pressure and the occurrence of micro-cracks, faults, and breakthroughs of the caprock. It can also be used to monitor and evaluate borehole integration caused by earthquake by monitoring any damage to the cementing and casing, which could lead to CO_2 leakage from the wellbore.

Technical problems of geophysical methods for monitoring CO_2 sequestration

The technical problems associated with the use of geophysical methods for CO_2 sequestration can be divided into the four aspects of acquisition, equipment, processing, and interpretation:

(1) Acquisition

Of fundamental importance is maintaining the same geometries and source and receiver locations. For example, in 4D seismic surveys, current onshore acquisition methods cannot realize repeatable shot and receiver locations for monitoring and baseline surveys. Nevertheless, as early as in the beginning of the second phase of the Weyburn project, geophysicists had thought to plant permanent geophones and to use a Vibroseis. However, the use of a Vibroseis in a monitoring survey produces seismic signal differences between the baseline dynamite sources and the Vibroseis monitoring.

In the Weyburn field, the baseline 3D seismic survey was acquired in December 1999, and the first 3D seismic monitoring survey was carried out in December 2001 after the injection of one million tons of CO_2. While the source and receiver locations of the 2001 monitoring survey were carried out as near as possible to the location of the 1999 baseline survey, in order to increase the seismic stacking fold, a swath of the baseline survey was split into two or three sections in the monitoring survey, as shown in Figure 7 (Ma et al., 2009). Even so, the seismic differences between the 2001 monitoring data and the 1999 baseline data were well within the post-stack seismic section (Li, 2003). The distribution of CO_2, as determined by the differences in the seismic amplitude map, was affected by the change in geometry. This is why, for 2002, the monitoring acquisition geometry was changed back to be consistent with that of the 1999 baseline (Table 1).

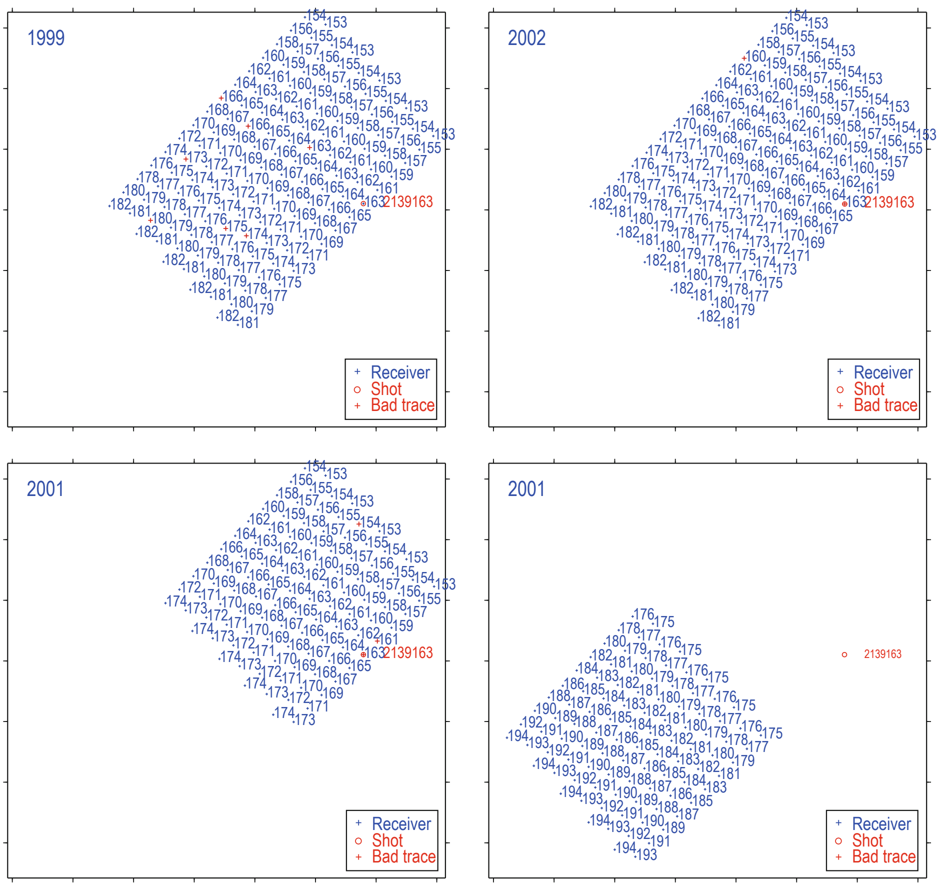

Fig.7 One swath shot of 2139163 in the 1999 baseline, 2001 monitoring, and 2002 monitoring surveys in the Weyburn field. Blue numbers indicate receiver locations and red numbers source locations. Note that the same source position was shot twice in 2001. As such, two swath shots in the 2001 monitoring survey can be combined into one swath shot, as that in the 1999 baseline and 2002 monitoring surveys.

In the Weyburn project, the biggest problem in subsequent seismic monitoring was that the CO_2 had migrated outside the baseline 3D seismic survey with greater volumes of CO_2 injection. Consequently, in CCS projects, the baseline 3D seismic survey area must be designed to be big enough so that the CO_2 plume does not move outside the 3D seismic monitoring area during long-term CO_2 injection. However, if we increase the area of a 3D seismic survey, the cost of 4D seismic acquisition and the investment necessary in the entire CCS project will also increase.

For CCS projects undertaken in China, only the Sinopec Shengli Oil Company has acquired a baseline and an overlaid 3D seismic survey in the Gao 89 CO_2-EOR area. The baseline 3D seismic survey was acquired in the winter of 1992 and the overlaid or monitoring 3D seismic survey was acquired in the winter of 2011. CO_2 injection began in 2007. By 2011, about 60,000 tons of CO_2 had been injected into the reservoir. However, the geometries of the baseline and overlaid 3D seismic surveys are quite different. The acquisition pattern in 1992 was 4 lines × 6 shots, the fold-coverage was 20, the common-depth-point (CDP) bin size was 25 × 100 m, and the sample rate was 4 ms. In 2011, the acquisition pattern was 18 lines × 12 shots, the fold-coverage was increased to 225, the CDP bin size was 25 × 25 m, and the sample rate was 2 ms. Besides, the source and receiver locations of the 1999 baseline 3D seismic survey did not coincide with those of the 2011 overlaid 3D survey.

Most depleted oil fields have 3D seismic data, so if we take the 3D seismic data acquired earlier as the baseline data when carrying out CO_2-EOR or sequestration, then the monitoring seismic acquisition parameters are often higher than those of the baseline, such as in high-density and wider azimuth acquisitions. It would not be an easy task to make the monitoring geometry match the baseline geometry. In addition, with the ongoing construction of a well site, including the installation of water, oil, CO_2, and sewage pipelines, monitoring seismic acquisition must be done very carefully when using a dynamite source. To avoid damaging the underground facilities of oil fields, dynamite source locations must be moved from their designed locations when acquiring monitoring seismic data, causing the source locations to be different from those of the baseline.

When acquiring monitoring 3D seismic data at the Gao 89 area in 2011, the geophysical crew asked the oil company to shut down the oil and CO_2 injection pumps at the well site in order to reduce background noise. This resulted in one of the four CO_2 injection wells never being able to be injected with CO_2 again. Similar things happened in the Jingbian field of the Shaanxi Yanchang Petroleum Group at its first CO_2 injection well 45543-03 (Figure 8). When the CO_2 source was changed from food-grade CO_2 to captured CO_2 from the Yulin Coal Chemical Factory, we temporarily stopped injecting CO_2. When we injected CO_2 again, the backwater was so strong from the borehole that CO_2 could not be injected. Two years later, this well could again be injected with CO_2, but the daily CO_2 injection volume is small (Figure 9). Therefore, stopping CO_2 injection during seismic acquisition can result in having to abandon the injection well. In our experience, when acquiring seismic data, particularly when acquiring monitoring seismic data, CO_2 and water injection wells should not be shut down. The bottom borehole pressure can be maintained at that of the injection or production pressures. For example, in the Weyburn field, CO_2 and water injection continues during the acquisition of monitoring seismic data.

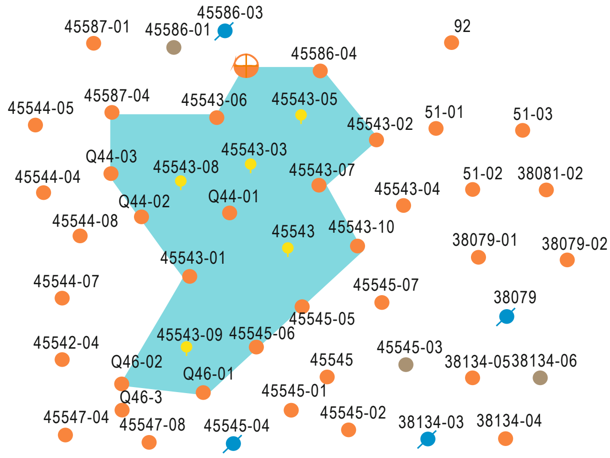

Fig.8 Well distributions of the Jingbian CCS Project of the Shaanxi Yanchang Petroleum Group (Ma et al., 2014). The yellow symbols indicate CO_2 injection wells; blue symbols water injection wells, and red solid circles producing wells.

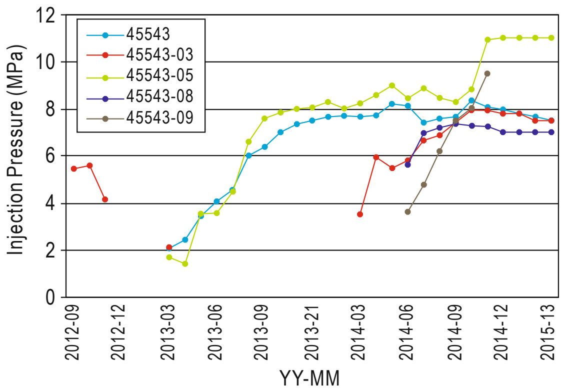

Fig.9 Injection pressure of five CO_2 injection wells in the Jingbian field of the Shaanxi Yanchang Petroleum Group (Ma et al., 2014). Note that the red line represents the first CO_2 injection well 45543-03. In September 2012, CO_2 injection began at this well, and then, following the replacement of the CO_2 source, it could not be injected further until March 2012.

Of course, if operations continue, well site pumping equipment produces loud noise during seismic data acquisition. For example, in the second CO_2-EOR and storage at a site of the Shaanxi Yanchang Petroleum Group, i.e., a 3D seismic baseline area of 10.68 km^2 was acquired in the Changguanmiao area of the Wuqi field. Oil and water injection pumping were not shut down during this acquisition, so the seismic data would reflect the pressure during production. However, the pumping noise interfered with the seismic signal and affected the quality of the seismic data (Figure 10).

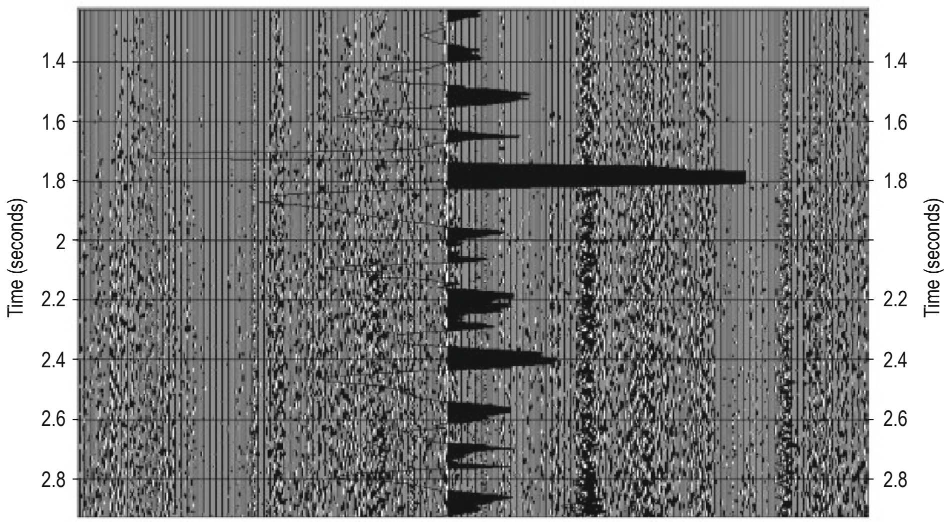

Fig.10 Typical pumping noise in a shot gather of a baseline 3D seismic survey in the Wuqi field.

In the Saskpower's Boundary Dam CCS saline aquifer storage site, 630 permanent receivers are embedded at a depth of 20 meters in a 6.25-km^2 area, in order to ensure consistent receiver locations for the 4D seismic survey. A Vibroseis truck was used in the monitoring seismic survey after CO_2 injection in April 2015. Prior to CO_2 injection, vintage baseline 3D seismic data was acquired in March 2012, April 2013, and November 2013 with a dynamite source. These three baseline 3D seismic datasets are used to evaluate the repeatability of the 4D seismic data acquisition and processing (Rostrona et al., 2014; White et al., 2014), and especially to evaluate the impact of seasonal variation on 4D seismic acquisition.

Before CO_2 injection, except for three baseline 3D seismic acquisition sessions, passive seismic, resistivity/magnetotelluric, gravity and other surface monitoring techniques were carried out in the saline aquifer storage site of the Boundary Dam power station. In the borehole, crosshole seismic, VSP, joint surface and borehole resistivity, online temperature and pressure monitoring, and borehole passive seismic monitoring techniques were performed. An advanced time-lapse logging technique was designed as well (White et al., 2014).

With respect to 4D seismic data acquisition for CO_2 sequestration, the optimal time interval of repeated 3D seismic monitoring and observation geometry surveys depends on costs. Seismic acquisition costs must be effectively reduced in order to decrease the cost of the entire CCS project. However, unlike 4D seismic monitoring for water flooding and steam injection for heavy recovery, the major reservoir for the CO_2 injection must be monitored as well as other reservoirs near the major reservoir and saline aquifers. This is because the injected CO_2 might leak into nearby reservoirs, so seismic monitoring is required to track and determine CO_2 leakage pathways. Furthermore, the optimal way to store CO_2 is in multiple reservoir units and aquifers, also known as the stack storage method. Using this storage method, we can effectively reduce the investment associated with geological, geophysical, drilling, and other investigations. As such, these nearby reservoirs and aquifer parameters must be studied as an integral part of major oil and gas reservoirs. So, when acquiring 4D seismic monitoring data, the acquisition parameters must be taken into account, particularly the stacking fold of the major reservoir and its nearby reservoirs, which may increase the cost of seismic acquisition.

(2) Geophysical equipment

The majority of geophysical monitoring equipment for conventional oil and gas exploration can be used in CO_2 sequestration. However, the research and development of a borehole monitoring device for CO_2

injection, production, and monitoring wells has taken the technical high ground in equipment development. Online monitoring data in the borehole may include the VSP, temperature, pressure, and time lapse logs. These instruments must be placed at different well depths and require miniaturization, high-temperature resistance, and corrosion protection from carbonic acid, as they must be placed permanently in the borehole. This is because the monitoring of reservoir parameters from the borehole may continue to be required after the CO_2 sequestration project is completed. These parameters are very important in calibrating seismic monitoring data and making well log corrections post-closure of the CO_2 sequestration.

The current temperature and pressure monitoring method is to sink monitoring instruments into the bottom of the borehole and pull them out to read data after a period of CO_2 injection. While VSP and time-lapse well logging are currently only carried out in monitoring wells, if they could be carried out in CO_2 injection wells, we could obtain more accurate and valuable reservoir parameters at these wells under high-pressure conditions.

From the Weyburn Project, we learned the importance of geophysicists using fiber optic geophones and permanently burying them behind the casing to measure VSP, as they did in the Boundary Dam aquifer storage site (White et al., 2014). The fiber optic geophone is small, has high sensitivity, has strong anti-electromagnetic interference, can withstand high temperature and pressure, has no electrical leakage, and is easy to reuse. It may be used to achieve permanent, real-time online measurement. Crosswell resistivity monitoring is also facing equipment problems with respect to online monitoring in the well during CO_2 injection.

(3) Data Processing

In 4D seismic data processing for CO_2 sequestration, the objective is to obtain the differences between repeated seismic surveys, and then use these seismic differences to determine the effects of CO_2-EOR, CO_2 distribution underground, and abnormal pressure distributions, and to confirm the safety of the CO_2 storage. Since P-wave velocity obviously declines in the reservoir after CO_2 injection, it should be easy to measure the seismic differences before and after CO_2 injection. This does not mean that we can process reasonable seismic differences. When processing 4D seismic data, we should attribute different processing flows to the characteristics of the seismic data. These processing methods are not unique.

In the Weyburn field (Ma et al., 2009), although 3D seismic acquisition was carried out in December, we see that the first arrivals are different at the same source and same receiver locations of the vintage 3D seismic shot gathers (Figures 11 and 12). For this reason, we must calculate the average first-break differences between the baseline and monitoring 3D seismic data, and correct the first arrival data by applying the average first-break differences to the monitoring seismic data so that the baseline and monitoring data have the same first-break. Thus, we can process vintage 3D seismic data sets separately using the same processing flow.

To ensure that the vintage poststack seismic profiles are comparable, we applied the static correction of the baseline (1999) data sets to that of the monitoring data sets after making the first-arrival correction, and vice versa. Only the data quality of the static correction of the baseline was better than those of the monitoring data sets in the Weyburn field.

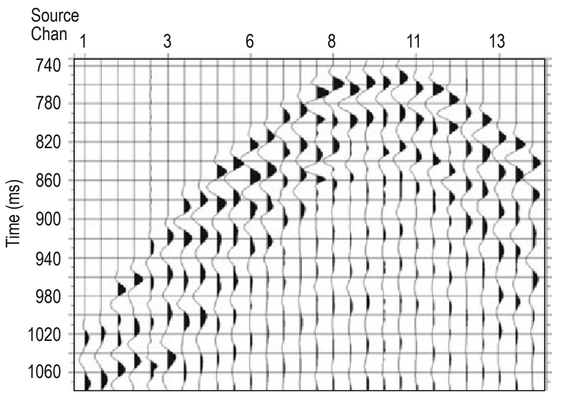

Fig.11 Comparison of the same shot gathers by inserting them into the display. The first trace was acquired in 1999, the second trace in 2001, and so on.

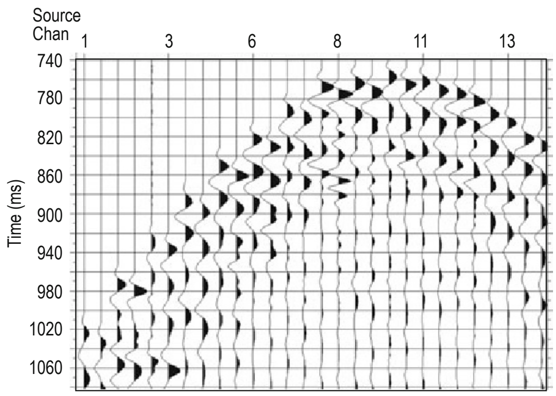

Fig.12 Comparison of the same shot gathers by inserting them into the display. The first trace was acquired in 1999, the second trace in 2002, and so on.

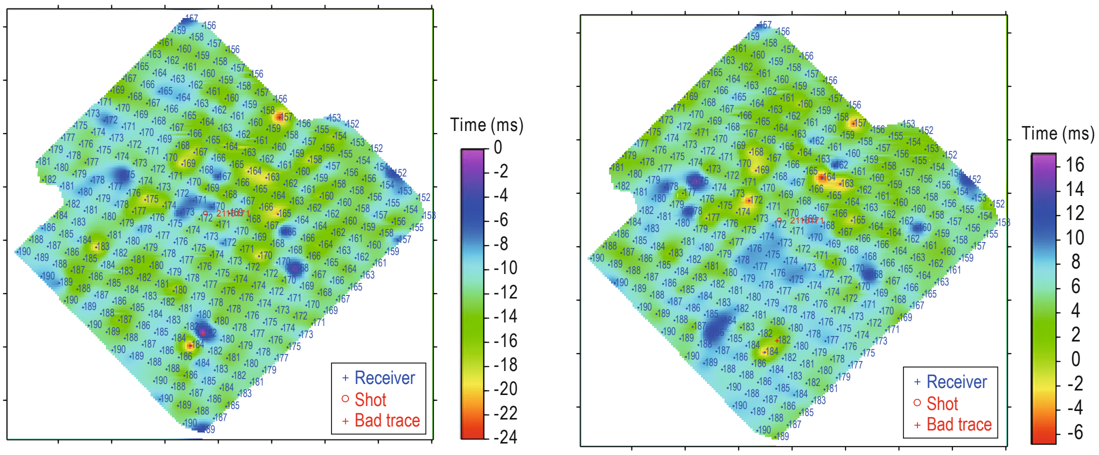

Fig.13 Differences in the first arrival for the same shot (2116171) between the baseline and monitoring 3D seismic data sets in the Weyburn field. Left: first arrival of 2001 (Monitor) minus that of 1999 (baseline); right: first arrival of 2002 (Monitor) minus that of 1999 (baseline).

When separately calculating the static correction of the baseline and monitoring 3D seismic data sets, we found their differences to be quite large. Such large differences in the static correction also affects the comparison of the vintage common midpoint (CMP) gathers and poststack seismic data. In Figures 14 and 15, we compared the differences in the static correction in the vintage seismic data sets acquired in 1999, 2001, and 2002 without any first-arrival correction. The differences in the static correction between the baseline and monitoring 3D seismic data are relatively large. Given these large differences in the static corrections, if we applied the same static corrections from either the baseline or monitoring data to both the baseline and monitoring data, this would cause large errors in the data even if we had applied first-arrival correction. Such errors would lead to the need for a larger residual static correction, and this might lead to new errors in the seismic amplitude and other attributes.

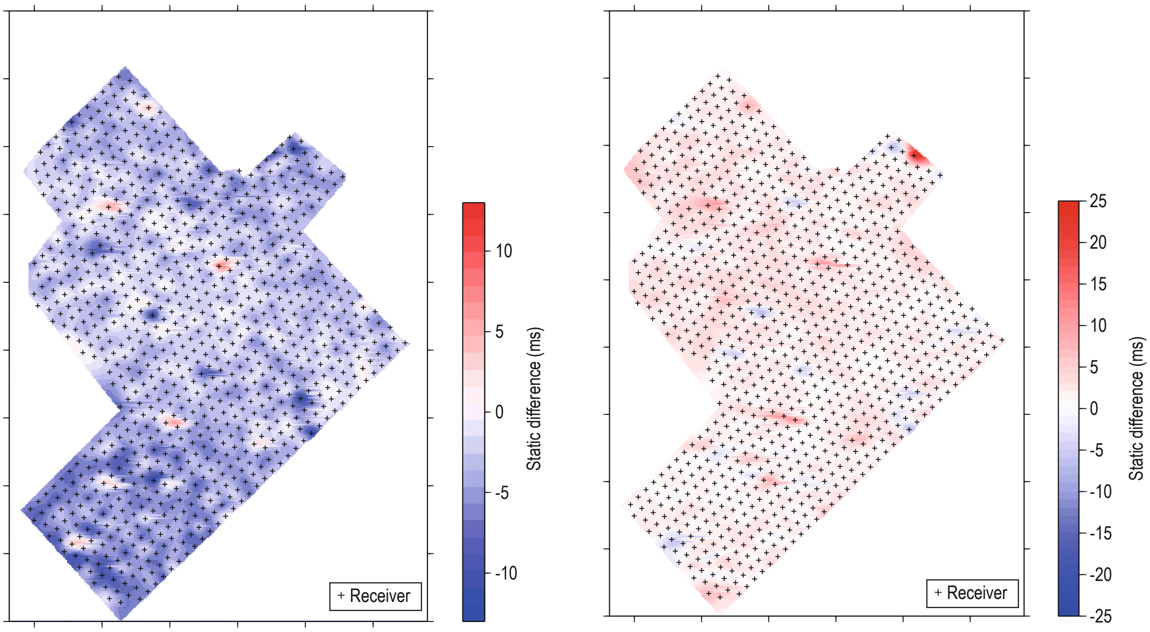

Fig.14 Differences in receiver static corrections between the baseline and monitoring data sets in the Weyburn field (Ma et al., 2009). Left: 1999 (baseline) minus 2001 (monitoring); right: 1999 (baseline) minus 2002 (monitoring).

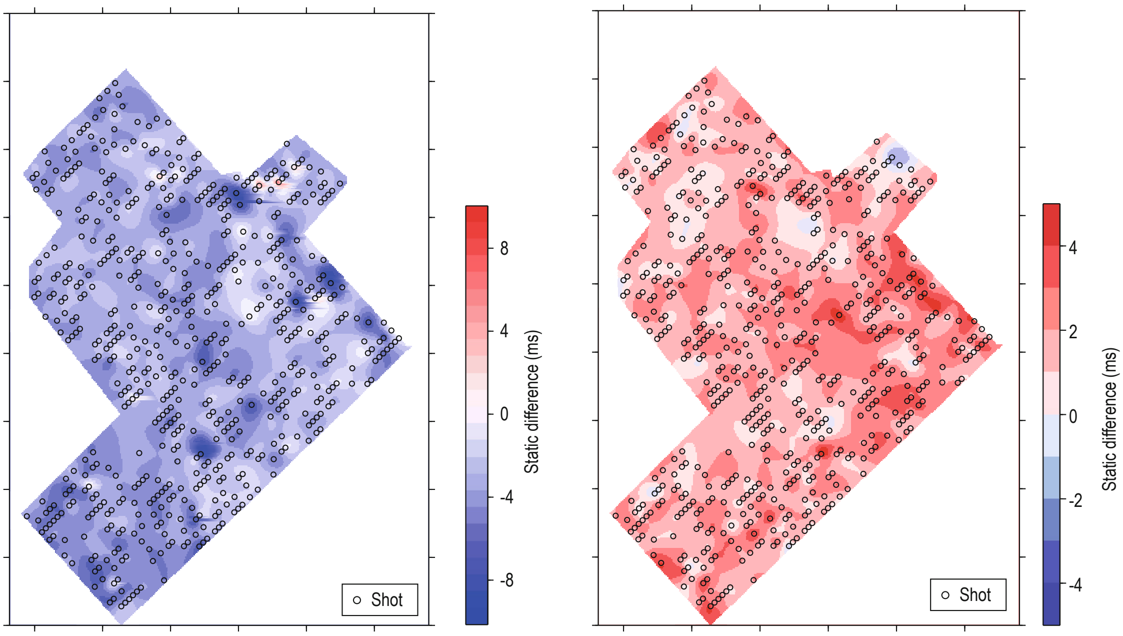

Fig.15 Differences of source static correction between the baseline and monitoring data sets in the Weyburn field (Ma et al., 2009). Left: 1999 (baseline) minus 2001 (monitoring); right: 1999 (baseline) minus 2002 (monitoring).

When the acquisition interval between repeated 3D seismic surveys is not long, the differences in the static corrections should not be large. However, if the acquisition interval is longer, so will be the differences in the static corrections. For example, in the Gao 89 area of the Sinopec Shengli oil field, baseline 3D seismic data was acquired in 1992, and the overlaid (monitoring) 3D seismic data was acquired in 2011. The larger static correction differences in the baseline and monitoring data that occurred in such a long interval are likely mainly caused by the declining water table. Increasing temperature has led to climate change and ground water evaporation, and the overexploitation of ground water has also resulted in the continuous drawdown of the water table. This situation is particularly serious in the north and northwest of China. The water table in many areas of the Ordos Basin in northwest China has dropped 50−100 meters or more. This decline in the water table will result in a frequency change in the seismic data in vintage seismic data acquisitions.

A change in the seismic sources will directly affect the results of the 4D seismic data processing. For example, in Australia's CO2CRC Otway Project, baseline 3D seismic data was acquired in January 2008 using a hammer source, while monitoring 3D seismic data was acquired in 2009 after injecting 35,000 tons of CO_2 using a Vibroseis (Urosevic et al., 2010; Pevzner et al., 2011). For the sake of maintaining the same source locations and to minimize environmental damage, the Vibroseis should become the predominant source in CO_2 sequestration projects. However, it is still difficult to completely remove harmonic noise in the current seismic processing method when using the Vibroseis. Hammer et al. (2004) compared Vibroseis and explosive shot gathers generated at the same source location, from which we can see the differences caused by different sources (Figure 16). Therefore, the differences associated with the use of Vibroseis, explosive, and other hammer sources may result in errors in 4D seismic interpretation.

Processing and comparisons of repeated 3D seismic data sets could be carried out for shot gathers, CMP gathers, and poststack and migrated data sets. Ideally, repeated seismic data sets should be compared with shot gathers. That is, if amplitude changes and travel-time delays caused by CO_2 injection could be observed or processed by the comparison of shot or CMP gathers, then subsequent pre-stack seismic inversions could produce better results. However, in actual 4D seismic data acquisitions, even if the source and receiver locations can be repeated before and after CO_2 injection, the impact of bad traces, pumping interference, and the interference of alternating currents on each 3D seismic survey will not be the same. Thus, with interference noise occurring at different traces, bad traces in the baseline data would not correspond to those in the monitoring data. Baseline bad traces may correspond to monitoring normal traces, and vice versa, and cause difficulties in making comparisons of repeated shot or CMP gathers.

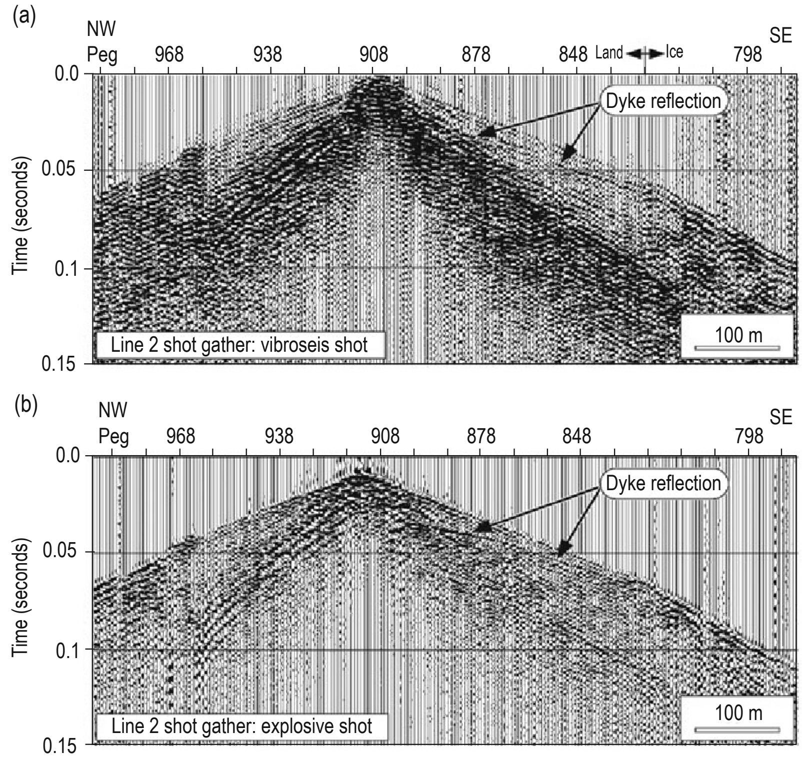

Fig.16 Comparison of Vibroseis and explosive shot gathers (Hammer et al., 2004).

CDP traces of repeated poststack and migrated seismic data can correspond, which will make it easy to perform cross-equalization and other comparisons. However, the ability to evaluate the effect of 4D seismic data monitoring and processing is dependent on whether the 4D seismic processing results are consistent with those of geological analysis, CO_2 flooding, tracing of CO_2, geochemical analysis, and reservoir numerical simulation.

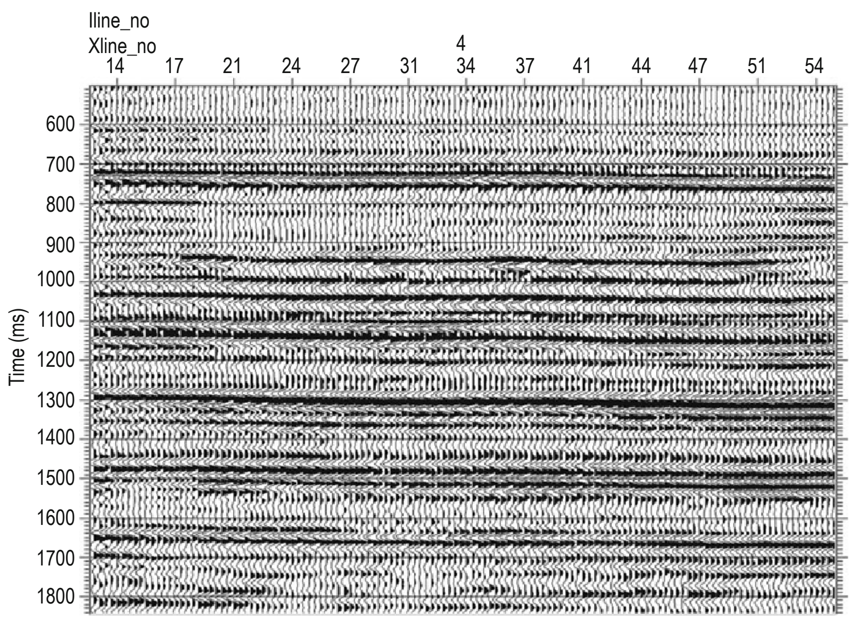

Fig. 17 Comparison of poststack 3D seismic baseline and monitoring data in the Weyburn field, where the first trace is 1999 baseline data, the second trace is 2001 monitoring data, and the third trace is 2002 monitoring data. The top of Marly unit is around 1140 ms.

This is the most difficult challenge in 4D seismic monitoring and processing. Sometimes, in our experience, even after processing 4D seismic data multiple times, we still could not achieve satisfactory results.

Often, the evaluation results of 4D seismic processing is affected by the available geological knowledge during CO_2 flooding. For example, it is generally believed that CO_2 saturation is high near an injection well. While 4D seismic differences must show anomalies near injection wells, the injected CO_2 might not be gathered near the injection well, and could have migrated elsewhere along a highly porous, fractured channel or a quick breakthrough. If the CO_2 injection region has a certain level of geological structure, the CO_2 will migrate to the high point of the structure. In this case, 4D seismic differences in the vicinity of the injection well might not be observed. It is also likely that when 4D seismic differences cannot be observed, the injected CO_2 could have broken through the caprock and moved into the aquifer near the major oil reservoir.

It is tricky to process baseline and monitoring 3D seismic data with different geometries. In this case, we may use geometry degradation or other methods to make the baseline and monitoring 3D geometries consistent. Or, we may make baseline CMP traces correspond to those of the monitoring data. Then, 4D seismic processing can be carried out.

(4) Interpretation

The goal of seismic interpretation for CO_2 sequestration is to eliminate interference from the seismic differences in order to identify the CO_2 and pressure distributions. The ultimate goal is to use seismic information to verify whether the amount of injected CO_2 equals the amount of the carbon stored. If the amount of CO_2 injected does not equal the amount of stored CO_2, we must determine from the 4D seismic information whether CO_2 leakage occurred, where it originated, whether the CO_2 is leaking into nearby saline aquifers, and whether the CO_2 is trapped by the secondary seals or is leaking to the surface.

4D seismic interpretation includes baseline and monitoring data and differential data interpretation. In this case, synthetic seismograms must be made to calibrate these data, respectively. In the absence of time-lapse logging data, an important step in the 4D seismic data calibration and interpretation becomes the prediction of well logs with the CO_2 injection pressure and saturation at the seismic monitoring stages. To do so, well curves are logged at the baseline stage to predict the compressional and shear wave velocities and the density at the monitoring stages using fluid substitution methods. However, when there is no time-lapse well logging data, it is difficult to estimate CO_2 saturation near injection wells. For reservoirs with natural or hydraulic fractures, the difficulty of well log prediction is how the open or closed micro-fractures caused by the injection or production pressures will impact the compressional, shear wave, and density logs (Shen et al., 2009; Wei et al., 2013).

The greatest difficulty in 4D seismic interpretation is determining how to obtain CO_2 saturation and pore pressure from the amplitude differences and time-delay information (Ivanova et al., 2012; Grude et al., 2013). Amplitude variation with offset (AVO) inversion, acoustic impedance inversion, elastic impedance inversion and other reservoir prediction technologies are the main methods for obtaining these parameters (Lumley, 2010; Meadows and Cole, 2013; Gong et al., 2013; Huang et al., 2015). However, it is difficult to discriminate between the impacts of CO_2 saturation and pore pressure in seismic difference data when using only compressional wave information. Taking into account that shear velocity is not sensitive to fluid saturation, the use of joint compressional and converted wave interpretation, and the use of 4D-converted wave information to predict pore pressure may be one solution for predicting pore pressure (Yang et al., 2015).

Binding and mashing the results of numerical reservoir simulation is an important method in 4D seismic interpretation (Huang et al., 1997; Johnston, 2013; Riazi et al., 2013). Numerical reservoir simulation can be used to predict the characterization of CO_2 migration, distribution, and storage. It can also be used to predict the actual CO_2 sequestration capacity as well. We may obtain the CO_2 saturation and pressure distribution from numerical reservoir simulation. When the CO_2 saturation and pressure effects cannot be distinguished from the 4D seismic data, and the seismic data resolution is not enough to distinguish thin interbed and reservoir vertical heterogeneity, the CO_2 sweep range and CO_2 saturation and pore pressure distribution models provided by numerical reservoir simulation can be verified and improved from 4D seismic monitoring data. Then, the CO_2 saturation volume can be obtained to calculate the CO_2 sequestration capacity and reservoir pressure volume to predict the risk of CO_2 leakage.

For example, from the amplitude differences of the Marly unit in the Weyburn field (Figure 1), it is difficult to explain the CO_2 sweep efficiency and CO_2 sequestration capacity. In fact, there are 16 CO_2-EOR patterns in the Phase 1A area (White et al., 2004). Different patterns have different CO_2 flooding efficiencies. Although the CO_2 flooding patterns differ, their 4D seismic responses are similar. This is a characteristic non-uniqueness of 4D seismic difference data. Through numerical reservoir simulation, we can establish the correct reservoir model and reduce the non-uniqueness of 4D seismic interpretation.

Considering that injected CO_2 could leak into a nearby saline aquifer, it is necessary to make a saline aquifer prediction, which is similar to reservoir prediction, in order to estimate both the amount of CO_2 that might leak into the saline aquifers and the pore pressure. Then, we can determine whether the caprock for the saline aquifer is safe and whether there is the risk that the pore pressure is high enough to break the caprock and cause the CO_2 to continue to move upward. Consequently, rock physics experiments, fluid substitution, and other methods applied in major reservoirs are also required in the study of upper saline aquifers.

Technically speaking, conventional 3D seismic interpretation techniques are suitable for 4D seismic interpretation. Currently, some interpretation methods for CO_2 sequestration are being tested and explored, such as seismic attributes, absorption, and attenuation.

Of course, the comprehensive utilization of other geophysical information, such as the inverted density from repeated gravity monitoring, the inversion of CO_2 saturation by the resistivity method, locating fractures from microseismic monitoring, and making geophysical results consistent with those from other disciplines and technologies will all help to improve the accuracy of 4D seismic interpretation.

Conclusions

Geophysical techniques, especially 4D seismic monitoring, are the most effective and reliable techniques for the measurement, monitoring, and verification of CO_2 sequestration. They represent the most important aspect of the safety monitoring system of entire CCS projects.

The greatest value in carrying out CO_2-sequestration geophysical monitoring using oil and gas geophysical methods is to improve the accuracy of existing geophysical methods in reservoir prediction. This means that conventional reservoir prediction is used to predict unknown oil and gas reserves. The predicted oil and gas reserves might vary greatly from the actual reserves. A very long period of oil and gas exploitation is required to confirm the presence of predicted reserves. However, reservoir prediction for CO_2 sequestration is used to determine the amount of potential CO_2 storage or injection and geophysical methods are used to predict the known CO_2 reserves. These existing geophysical methods must be amended or improved with respect to known targets.

Geophysical monitoring is required prior to CO_2 injection, during injection, and after site closure. It takes a long time to monitor the safety of CO_2 sequestration. The quality and effectiveness of 4D seismic monitoring is directly affected by the acquisition methods used, the monitoring equipment used, and the surface conditions. Processing 4D seismic data requires different processing flows depending on the observed geometries and seismic source types. The interpretation of 4D seismic data requires consistency with the fields and techniques of geology, well logging, determinations of CO_2 flooding effect, and numerical reservoir simulation. Acquisition, processing, and interpretation involve many problems that must be resolved. The primary challenge is how to measure, monitor, and verify the safety of CO_2 sequestration using advanced equipment, while realizing the lowest cost and designing the best monitoring program. This brings new challenges in the development of geophysical equipment, data processing, and interpretation techniques.

With the global demand to cut carbon emissions and the urgent need to address climate change, CCS technology is currently the most direct and effective method for rapidly reducing carbon emissions and is currently facing unprecedented opportunities for development. The Chinese government has promised to reach a peak in its carbon emissions by 2030 and will launch a national cap and trade plan in 2017. This will bring great opportunities for the development of CCS technology in China. With more CCS projects being put into operation, geophysical monitoring for CO_2 sequestration will bring more opportunities for geophysical applications. The upcoming release of the International Organization for Standardization's (ISO's) standards regarding carbon dioxide capture, transportation, and geological storage (ISO/TC265) will reflect the essential nature of geophysical monitoring in CCS projects. With CCS, traditional geophysical techniques for oil and gas exploration and resource exploration have been given a new mission to expand their range and application.

Acknowledgements

With thanks for the support from the Shaanxi

Yanchang Petroleum Group, Geophysical Research Institute of Sinopec Shengli Oilfield, Geophysical Research Institute and Geophysical Company of Sinopec Zhongyuan Oilfield. We also express our sincere thanks to Professor Huang Xuri for his critical and constructive comments on the paper.

References

Alnes, H, Eiken, O., Nooner, S., and Sasagawa, G., 2011, Results from Sleipner gravity monitoring: updated density andtemperature distribution of the CO_2 plume. Energy Procedia, **4**, 5505–5511.

Bergmann, P., Schmidt-Hattenberger, C., Kiessling, D., Rücker, C., Labitzke, T., Henninges, J., Baumann, G., and Schütt, H., 2012, Surface-downhole electrical resistivity tomography applied to monitoring of CO_2 storage at Ketzin, Germany: Geophysics, **77**(6), B253–B267.

Bikle, M. J., 2009, Geological carbon storage: Nature Geoscience, **2**, 815–818.

Brown, L. T., 2002, Integration of rock physics and reservoir simulation for the interpretation of time-lapse seismic data at Weyburn Field, Saskatchewan: Master's thesis, Colorado School of Mines.

Calvert, R., 2005, Insights and methods for 4D reservoir monitoring and characterization: SEG Distinguished Instructor Short Course, DISC series, **8**, 2–3.

Chadwick, A., Williams, G., Delepine, N., Clochard, V., Labat, K., Sturton, S., Buddensiek, M., Dillen, M., Nickel, M., Lima, A. L., Arts, R., Neele, F., and Rossi, G., 2010, Quantitative analysis of time-lapse seismic monitoring data at the Sleipner CO_2 storage operation: The Leading Edge, **29**(2), 170–177.

Chinese Government, 2015, China-U.S. Joint Presidential Statement on Climate Change: http://www.gov.cn/xinwen/2015-09/26/content_2939222.htm

Chu, S., 2009, Carbon capture and sequestration, Science, **325**, 1599.

CSLF-Carbon Sequestration Leadership Forum, Active and Completed CSLF Recognized Projects, 2015. http://www.cslforum.org/projects/jingbian_ccs.html

Davis, T. L., Terrell, M. J., Benson, R. D., Cardona, R., Kendall, R. R., and Winarsky, R., 2003, Multicomponent seismic characterization and monitoring of the CO_2 flood at Weyburn Filed, Saskatchewan: The Leading Edge, **22**(7), 696–697.

Finley, R. J., 2014, An overview of the Illinois Basin –Decatur project: Greenhouse Gases: Science and Technology, **4**(5), 571–579.

Gasperikova, E., and Hoversten, G. M., 2008, Gravity monitoring of CO_2 movement during sequestration: Model studies: Geophysics, **73**(6),WA105–WA112.

Gong, X., Zhang, F., Li, X., and Chen, S., 2013, Study of S-wave ray elastic impedance for identifying lithology and fluid: Applied Geophysics, **10**(2), 145–156.

GCCSI-The Global CCS Institute, 2014, The Global Status of CCS: http://www.globalccsinstitute.com/publications/global-status-ccs-2014

Grude, S., Landrø, M., and Osdal, B., 2013, Time-lapse pressure–saturation discrimination for CO_2 storage at the Snøhvit field: International Journal of Greenhouse Gas Control, **19**, 369–378.

Hammer, P. T. C, Clowes, R. M., and Ramachandran, K., 2004, High-resolution seismic reflection imaging of a thin,diamondiferous kimberlite dyke: Geophysics, **69**(5), 1143–1154.

Hao, Y., and Yang, D., 2012, Research progress of carbon dioxide capture and geological sequestration problem and seismic monitoring research: Progress in Geophysics (in Chinese), **27**(6), 2369–2383.

He, Y., Zhang, B., Duan, Y., Xue, C., Yan, Q., He, C., and Hu, T., 2014, Numerical Simulation of Surface and Downhole Deformation Induced by Hydraulic Fracturing: Applied Geophysics, **11**(1), 63–72.

Huang, H., Wang, Y., Guo, F., Zhang, S., Ji, Y., and Liu, C., 2015, Zoeppritz equation-based prestack inversion and its application in fluid identification: Applied Geophysics, **12**(2), 199–211.

Huang, X., Meister, L., and Workman, R., 1997, Reservoir Characterization by Integration of Time-lapse Seismic and Production Data: SPE-38695, SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 5 –8 October.

IEA-International Energy Agency, 2013, Technology Roadmap: Carbon Capture and Storage 2013 edition. http://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2013.html.

IPCC-Intergovernmental Panel on Climate Change, 2014, IPCC Climate Change 2014 Synthesis Report, *in* Core Writing Team, Pachauri, R. K., and Meyer, L., Eds: Cambridge Univ. Press. http://www.ipcc.ch/report/ar5/syr/

Ivanova, A., Kashubin, A., Juhojuntti, N., Kummerow, J., Henninges, J., Juhlin, Ch., Lüth, S., and Ivandic, M., 2012, Monitoring and volumetric estimation of injected CO_2 using 4D seismic, petrophysical data, core measurements and well logging: a case study at Ketzin: Germany: Geophysical Prospecting, **60**(5), 957–973.

Johnston, D. H., 2013, Practical applications of time-lapse seismic data: 2013 SEG Distinguished Instructor Short

Course, DISC series, **13**, 181–183.

Kiessling, D., Schmidt-Hattenberger, C., Schuett, H., Schiling, F., Krueger, K., Schoebel, B., Danckwardt, E., and Kummerow, J., 2010, The CO2SINK GROUP, Geoelectrical methods for monitoring geological CO_2 storage, First results from crosshole and surface-downhole measurements from the CO2SINK test site at Ketzin (Germany): International Journal of Greenhouse Gas Control, **4**, 816–826.

Kim, J., Matsuoka, T., and Xue, Z., 2011, Monitoring and detecting CO_2 injected into water-saturated sandstone with joint seismic and resistivity measurements: Exploration Geophysics, **42**(1), 58–68.

Lawton, D., 2010, Carbon capture and storage: opportunities and challenges for geophysics: CSEG Recorder, **35**(6), 7–10.

Li, G., 2003, 4D seismic monitoring of CO_2 flood in a thin fractured carbonate reservoir: The Leading Edge, **22**(7), 690–695.

Lumley, D., 2010, 4D seismic monitoring of CO_2 sequestration: The Leading Edge, **29**(2), 150–155

Ma, J., Gao, L., and Morozov, I. B., 2009, Time-lapse repeatability in 3C-3D dataset from Weyburn CO_2 sequestration project: 2009 Canadian Society of Exploration Geophysicists CSEG/CSPG/CWLS Convention, AVO. Calgary, Canada.

Ma, J., and Morozov, I. B., 2010, AVO modeling in of Pressure-Saturation effects in Weyburn CO_2 Sequestration: The Leading Edge, **29**(2), 178–183.

Ma, J., Wang, X., Gao, R., Zhang, X., Wei, Y., Wang, Z., Ma, J., Huang, C., Zhao, X., Jiang, S., Liu, L., Li, L., Yu, H., and Wang, H., 2014, Jingbian CCS Project, China: Second Year of Injection, Measurement, Monitoring and Verification: Energy Procedia, **63**, 2921–2938.

Ma, J., and Zhang, X., 2010, Geophysical methods for monitoring CO_2 sequestration: Status, challenges and countermeasures: China Population Resources and Environment, 2010 China Sustainable Development Forum Special Issue, **20**, 223–228.

Martínez, J. M., and Schmitt, D. R., 2013, Anisotropic elastic moduli of carbonates and evaporates from the Weyburn-Midale reservoir and seal rocks: Geophysical Prospecting, **61**(2), 363–379.

Matter, J. M., and Kelemen, P. B., 2009, Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation: Nature Geoscience, **8**, 837–841.

Meadows, M. A., and Cole, S. P., 2013, 4D seismic modeling and CO_2 pressure-saturation inversion at Weyburn Field, Saskatchewan: International Journal of Greenhouse Gas Control, **16S**, S103–S117.

Mezghani, M., Fornel, A., Langlais, V., and Lucet, N., 2004, History matching and quantitative use of 4D seismic data for an improved reservoir characterization, SPE 90420, SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, 26–29 September.

Nakajima, T., and Xue, Z., 2013, Evaluation of a resistivity model derived from time-lapse well logging of a pilot-scale CO_2 injection site, Nagaoka, Japan: International Journal of Greenhouse Gas Control, **12**, 288–299.

NDRC-The National Development and Reform Commission of the People's Republic of China, A catalogue for national promoting key low-carbon technologies, 2014. http://www.sdpc.gov.cn/zcfb/zcfbgg/201409/t20140905_625023.html

NDRC-The National Development and Reform Commission of the People's Republic of China, 2015, Implementation guide for national promoting key low-carbon technologies: China Financial and Economic Publishing House.

Onishi, K., Ueyama, T., Matsuoka T., Nobuoka, D., Saito, H., Hiroyuki, A., and Xue, Z., 2009, Application of crosswell seismic tomography using difference analysis with data normalization to monitor CO_2 flooding in an aquifer: International Journal of Greenhouse Gas Control, **3**(3), 311–321.

Pevzner, R., Shulakova, V., Kepic, A., and Urosevic, M., 2011, Repeatability analysis of land time-lapse seismic data: CO2CRC Otway pilot project case study: Geophysical Prospecting, **59**(1), 66–77.

Reiner, D. M., 2016, Learning through a portfolio of carbon capture and storage demonstration projects: Nature Energy, **1**, 1–7, doi:10.1038/nenergy.2015.11

Riazi, N., Lines, L., and Russell, R., 2013, Integration of time-lapse seismic analysis with reservoir simulation, GeoConvention 2013, Calgary, Canada.

Roggero, F., Ding, D. Y., Berthet, P., Lerat, O., Cap, J., and Schreiber, P. E., 2007, Matching of production history and 4D seismic data -application to the Girassol Field, Offshore Angola, SPE109929, SPE Annual Technical Conference and Exhibition, Anaheim, California, USA, 11–14 November.

Rostrona, B., White, D., Hawkesc, C., and Chalaturnyka, R., 2014, Characterization of the Aquistore CO_2 project storage site, Saskatchewan, Canada: Energy Procedia, **63**, 2977–2984.

Samsonov, S., Magdalena, Czarnogorska, M., and White, D. J., 2015, Satellite interferometry for high-precision detection of ground deformation at a carbon dioxide storage site: International Journal of Greenhouse Gas Control, **42**, 188–199.

Service, R., 2009, Carbon sequestration: Science, **325**, 1644–1645.

Shen, X., Ma, J., and Pan, B., 2009, Pressure-dependent AVO response of fractured-aperture rock: CPS/SEG

2009 Conference and Exhibition, Geophysics' Challenge, Opportunity, and Innovation, April 25–27, Beijing, China.

Spetzler, J., Xue, Z., Saito, H., Nobuoka, D., Azuma, H., and Nishizawa, O., 2008, Case Story: Time-Lapse Seismic Crosswell Monitoring of CO_2 injected in an Onshore Sandstone Aquifer: Geophysical Journal International, **172**, 214–225.

Sun, S., 2006, Geological problems of CO_2 underground storage and its significance on mitigating climate change: China Basic Science, **8**(3), 17–22.

Ugalde, A., Villaseñor, A., Gaite, B., Casquero, S., Martí, D., Calahorrano, A., Marzán, I., Carbonell, R., and Estaún, A. P., 2013, Passive Seismic Monitoring of an Experimental CO_2 Geological Storage Site in Hontomín (Northern Spain): Seismological Research Letters, **84**(1), 75–84.

Urosevic, M., Pevzner, R., Kepic, A., Shulakova, V., Wisman, P., and Sharma, S., 2010, Time-lapse seismic monitoring of CO_2 injection into a depleted gas reservoir—Naylor Field, Australia: The Leading Edge, **29**(2), 164–169.

Verdon, J. P., Kendall, J., White, D., Angus, D. A., Fisher, Q. J., and Urbancic, T., 2010, Passive seismic monitoring of carbon dioxide storage at Weyburn: The Leading Edge, **29**(2), 200–206.

Verkerke, J. L., Williams, D. J., and Thoma, E., 2014, Remote sensing of CO_2 leakage from geologic sequestration projects: International Journal of Applied Earth Observation and Geoinformation, **31**, 67–77.

Wang, Z., Cates, M. E., and Langan, R. T., 1998, Seismic monitoring of a CO_2 flood in a carbonate reservoir: A rock physics study: Geophysics, **63**(5), 1604–1617.

Wei, J., Di, B., and Ding, P., 2013, Effect of crack aperture on P-wave velocity and dispersion: Applied Geophysics, **10**(2), 125–133.

White, D. J., 2009, Monitoring CO_2 storage during EOR at the Weyburn-Midale Field: The Leading Edge, **28**(7), 838–842.

White, D. J., Hirsche, K., Davis, T., et al., 2004, Theme 2: Prediction,Monitoring and Verification of CO_2 movements, *in* Wilson M., and Monea M, eds. IEA GHG CO_2 Monitoring and Storage Project Summary Report 2000–2004: PTRC, Regina.

White, D. J., 2012, Geophysical Monitoring in Hitchon, B. (Editor), Best Practices for Validating CO_2 Geological Storage: Geoscience Publishing, Canada, 155–210.

White, D. J., 2013, Seismic characterization and time-lapse imaging during seven years of CO_2 flood in the Weyburn field, Saskatchewan, Canada: International Journal of Greenhouse Gas Control, **16S**, S78–S94.

White, D. J., Roach, L. A. N., Roberts, B., and Daley, T. M., 2014, Initial Results from Seismic Monitoring at the Aquistore CO_2 Storage Site, Saskatchewan, Canada: Energy Procedia, **63**, 4418–4423.

Wills, P. B., Hatchell, P. J., and Hansteen, F., 2009, Practical seismic monitoring of CO_2 sequestration: 2009 SEG Summer Research Workshop, CO_2 Sequestration Geophysics, 23–27 August, Banff, Canada.

Xue, Z., and Lei, X., 2006, Laboratory study of CO_2 migration in water-saturated anisotropic sandstone: based on P-wave velocity imaging: Exploration Geophysics, **37**(1), 10–18.

Xue, Z., Tanase, D., and Watanebe, J., 2006, Estimation of CO_2 saturation from time-lapse CO_2 well logging in an onshore aquifer, Nagaoka, Japan: Exploration Geophysics, **37**(1), 19–29.

Yang, Y., Ma, J., and Li, L., 2015, Research progress of carbon dioxide capture and storage technique and 4D seismic monitoring technique: Advances in Earth Science, **30**(10), 1119–1126.

Zhang, L., Ren, B., Huang, H., Li, Y., Ren, S., Chen, G., and Zhang, H., 2015, CO_2 EOR and storage in Jilin oilfield China: Monitoring program and preliminary results: Journal of Petroleum Science and Engineering, **125**, 1–12.

Ma Jin-Feng graduated from Department of Applied

Geophysics, Changchun College of Geology in 1985. In 1991 and 1998, he earned his MS and Ph.D degree in Department of Geology, Northwest University. He is a professor of geophysics at Department of Geology, Northwest University. His main research interests are geophysical monitoring for CO_2 sequestration, seismic reservoir prediction.