International Journal of Greenhouse Gas Control 20 (2014) 223–229

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

# Time-lapse pre-stack seismic inversion with thin bed resolution for $CO_2$ sequestration from Cranfield, Mississippi

Rui Zhang[a,*], Mrinal K. Sen[b,c], Sanjay Srinivasan[d]

[a] Lawrence Berkeley National Laboratory, The University of Texas at Austin, United States
[b] Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, United States
[c] National Geophysical Research Institute, Hyderabad, India
[d] Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, United States

ARTICLE INFO

*Article history:*
Received 25 March 2013
Received in revised form 23 October 2013
Accepted 29 October 2013
Available online 5 December 2013

*Keywords:*
Cranfield
Time-lapse
Basis pursuit
Pre-stack inversion
$CO_2$ sequestration

ABSTRACT

Time-lapse surface seismic surveys have been used for $CO_2$ sequestration monitoring at Cranfield, Mississippi. The 3D time-lapse seismic data were recorded both before (2007) and after (2010) $CO_2$ injection. The injection interval is the lower Tuscaloosa sandstone formation, which appears as a thin layer and displays weak signature due to $CO_2$ injection in the post-stack seismic amplitudes. Previous studies have reported inversion of time-lapse acoustic impedances for $CO_2$ plume mapping. However, the acoustic impedances lack elastic information, which are more sensitive to the fluid variation. To address this, we applied a basis pursuit pre-stack inversion on time-lapse Amplitude Versus Angle (AVA) datasets to obtain elastic properties ($V_p$, $V_s$, density and $V_p-V_s$ ratio). The inverted elastic properties show improved resolution and provide reasonable fits to the well-log data. The temporal changes of inverted elastic properties provide a basis for mapping the $CO_2$ plume after three years' injection, demonstrating their effectiveness for a $CO_2$ sequestration study.

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## 1. Introduction

Monitoring is an important aspect of $CO_2$ sequestration, becoming increasingly critical for the assessment of risk in any future large-scale $CO_2$ storage. Time-lapse borehole and surface seismic methods have been used to monitor $CO_2$ movements within the earth. The time-lapse borehole seismic methods have been applied and shown to be effective in monitoring $CO_2$ movements close to existing wells (Onishi et al., 2009; Zhou et al., 2010; Daley et al., 2010, 2011; Ajo-Franklin et al., 2013). However, borehole measurements typically only provide information close to the wellbore and do not provide sufficient areal resolution. This necessitates the use of time-lapse (4D) surface seismic measurements, which can cover a large area. Time-lapse surface seismic surveys have been applied in many $CO_2$ storage projects around the global to monitor $CO_2$ plume migration (Arts et al., 2004; Chadwick et al., 2004, 2012; Shi et al., 2007; Würdemann et al., 2010; JafarGandomi and Curtis, 2012; Li et al., 2013; Zhang et al., 2013d), but the effective evaluation of subsurface fluid volume and associated saturation from time-lapse seismic datasets remains a challenging task. In addition to mapping a $CO_2$ plume migration, surface seismic method can also be utilized for studying other aspects of the geological storage of carbon dioxide. For example, Cairns et al. (2012) used time-lapse surface seismic method to analyze the trapping mechanisms acting on injected $CO_2$. The possibility of leakage is another important issue that must be addressed. Bohnhoff et al. (2010) and Shang and Huang (2012) implemented seismic modeling to monitor possible leakage from deep formations. Draganov et al. (2012) introduced a ghost wave based interferometry technique for subsurface $CO_2$ plume monitoring. Most of these studies are based on post-stack seismic amplitudes, which do not contain the elastic properties.

Pre-stack seismic data are often represented as amplitude-versus-offset (AVO), which can be used to derive subsurface elastic properties. Landrø, 2001 firstly introduced a methodology to discriminate pressure and fluid saturation variation from time-lapse AVO data and applied it to a data set from the Gullfaks field. Later, Kvam and Landrø(2005) carried out a study of the sensitivity of this method to pressure change. Veire et al. (2006) incorporated this method into a stochastic inversion framework for pressure and fluid saturation changes and applied it to data from the Gullfaks field. Duffaut and Landrø(2007) studied elastic properties of $V_p-V_s$ ratio for stress and consolidation relationship. The same methodology has also been applied to data from the Sleipner field (Ghaderi and Landrø, 2009; Evensen and Landrø, 2010). These field applications provide convincing evidence of the reliability and utility of time-lapse AVO information for monitoring fluid saturation and pressure changes at depth. In this paper, we are focus on

* Corresponding author. Tel.: +1 510 486 6742.

1750-5836/$ – see front matter. Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.ijggc.2013.10.032

the interpretation of time-lapse pre-stack inversion results for the monitoring of $CO_2$ plume migration following three years of injection at Cranfield.

## 2. Cranfield characterization

Cranfield, located in the southwest corner of Mississippi (Fig. 1(a)), was first discovered in the 1940's with production starting in the 1950's (Mississippi Oil Gas Board, 1966). The reservoir is in the lower Tuscaloosa Formation, appearing as a nearly circular anticline (Fig. 1(b)) with a central gas cap and an oil ring at a depth of approximately 3000 m. Production decreased sharply in the 1960s, leading to many enhanced oil recovery (EOR) projects. These EOR projects produced a bounty of regional geologic information and numerous abandoned wells for $CO_2$ injection. Based on its previous production, we assume that the injection interval of lower Tuscaloosa Formation was predominately saturated with brine before $CO_2$ injection began. The Gulf Coast Carbon Center (GCCC) at the Bureau of Economic Geology started $CO_2$ injection in 2008 together with a number of studies utilizing a variety of well-logging and seismic methods (Meckel and Hovorka, 2009; Hovorka et al., 2013). The time-lapse seismic survey for $CO_2$ sequestration study was focused on the northeast part of the anticline, as shown in the yellow area in Fig. 1(c). A pre-injection 3D seismic survey was acquired at 2007, before the first injection in July 2008. The injection has achieved rates greater than 1.2 million tonnes/year through 23 wells, with cumulative mass injected as of August, 2010 of 2.2 million metric tonnes, when the post-injection 3D seismic survey was acquired in September. Different kinds of in situ measurements have been recorded during the injection, including well-bore temperature, pore pressure, and confining pressure (Klicman et al., 1988; Hovorka et al., 2011; Tao et al., 2013a; Lu et al., 2013; Zhang et al., 2013a; Meckel et al., 2013). Two-way-travel (TWT) time has been mapped at the top of the lower Tuscaloosa Formation as shown in Fig. 1(d) that also shows the center of anticline at the lower left corner.

## 3. Time-lapse pre-stack seismic data

The time-lapse pre-stack seismic datasets at Cranfield, originally acquired and processed in offset domain, have been transformed into the angle domain, The angles range from 3 to 42°. Fig. 2 displays examples of the pre- and post- injection AVA gathers at inline-1084 (Fig. 2(a) and (b)). The close-up view of time-lapse AVA gathers at well-28, within the black dashed rectangles in Fig. 2(a) and (b), are shown in Fig. 2(c) and (d). The sonic log data (red curves) from well-28 is inserted at its location. The injection interval is highlighted in yellow. It appears that the injection interval is buried within the negative amplitudes, making it difficult to identify this thin layer clearly in a conventional pre-stack AVA inversion. We also notice that strong phase and frequency variation in the angle domain, which could affect stability of the inversion results.

Log data at well-28, including $V_p$, $V_s$ and density (left three columns in Fig. 3), measured only before $CO_2$ injection, are shown with post-stack seismic well tie (middle three columns in Fig. 3), and pre-stack synthetic and real time-lapse gathers at this well location (right three columns in Fig. 3). The pre-stack synthetic gather is generated using an exact plane wave solution with the critical angle effect indicated by black arrows. The injection interval, indicated by a red arrow, appears as a thin layer of thickness of about 15 m and can be interpreted as permeable brine sandstone formation. The post-stack seismic well tie is also shown in the middle column of Fig. 3, the data has very good cross-correlation of 0.78 between the synthetic (blue) and the extracted (red) seismograms. The extracted seismogram is the seismic trace from the 3D post-stack seismic volume at the well-28 location. Such good post-stack seismic well tie demonstrates a reliable time-depth relationship

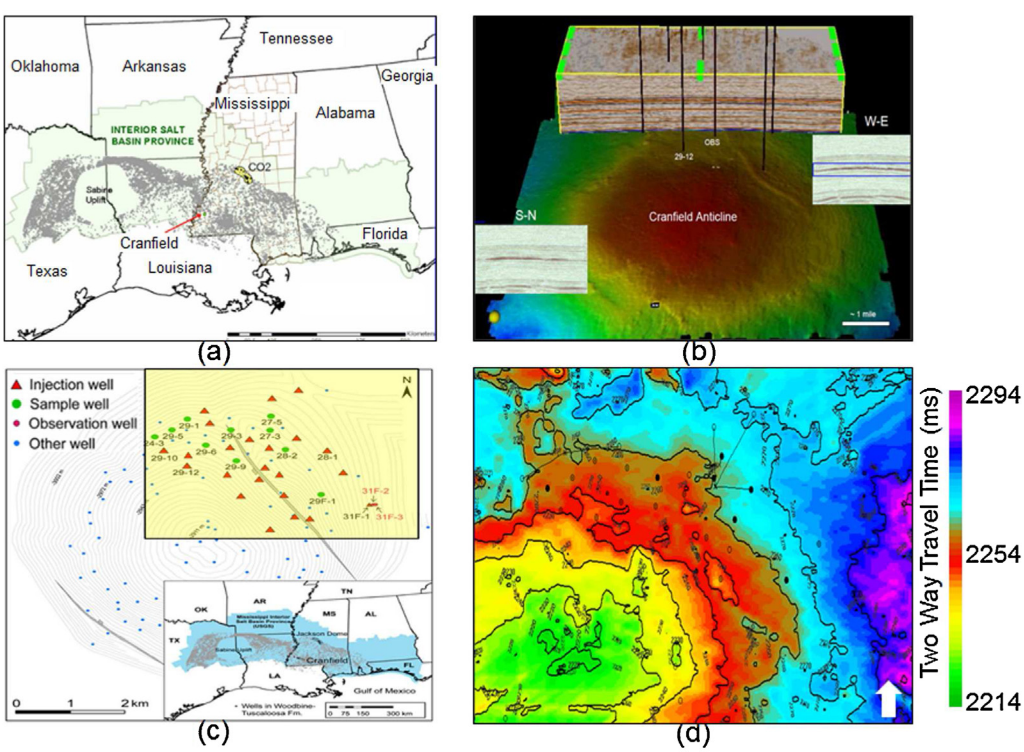


**Fig. 1.** Overview of Cranfield. (a) Map location of Cranfield; (b) surface mapping using vintage seismic data at the top of the complete anticline of the lower Tuscaloosa Formation; (c) coverage of the new time-lapse seismic datasets (yellow area) with 23 injection wells labeled as red triangles; (d) two-way-travel time contour map at the top of the injection interval (Choi et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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