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Monitoring CO_2 Storage at Cranfield, Mississippi with Time-Lapse Offset VSP – Using Integration and Modeling to Reduce Uncertainty

Thomas M. Daley[1*], Joel Hendrickson[2], John H. Queen[3]
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[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, 94720, USA
[2]Steelhead Geophysical LLC
[3]Hi-Q Geophysical Inc.

Abstract

A time-lapse Offset Vertical Seismic Profile (OVSP) data set was acquired as part of a subsurface monitoring program for geologic sequestration of CO_2. The storage site at Cranfield, near Natchez, Mississippi, is part of a detailed area study (DAS) site for geologic carbon sequestration operated by the U.S. Dept. of Energy's Southeast Regional Carbon Sequestration Partnership (SECARB). The DAS site includes three boreholes, an injection well and two monitoring wells. The project team selected the DAS site to examine CO_2 sequestration multiphase fluid flow and pressure at the interwell scale in a brine reservoir. The time-lapse (TL) OVSP was part of an integrated monitoring program that included well logs, crosswell seismic, electrical resistance tomography and 4D surface seismic. The goals of the OVSP were to detect the CO_2 induced change in seismic response, give information about the spatial distribution of CO_2 near the injection well and to help tie the high-resolution borehole monitoring to the 4D surface data.

The VSP data were acquired in well CFU 31-F1, which is the ~3200 m deep CO_2 injection well at the DAS site. A preinjection survey was recorded in late 2009 with injection beginning in December 2009, and a post injection survey was conducted in Nov 2010 following injection of about 250 kT of CO_2. The sensor array for both surveys

* Corresponding author. Tel.: +1-510-486-7316; fax: +1-510-486-5686.
E-mail address: tmdaley@lbl.govD

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was a 50-level, 3-component, Sercel MaxiWave system with 15 m (49 ft) spacing between levels. The source for both surveys was an accelerated weight drop, with different source trucks used for the two surveys.

Consistent time-lapse processing was applied to both data sets. Time-lapse processing generated difference corridor stacks to investigate CO_2 induced reflection amplitude changes from each source point. Corridor stacks were used for amplitude analysis to maximize the signal-to-noise ratio (S/N) for each shot point. Spatial variation in reflectivity (used to ‘map’ the plume) was similar in magnitude to the corridor stacks but, due to relatively lower S/N, the results were less consistent and more sensitive to processing and therefore are not presented. We examined the overall time-lapse repeatability of the OVSP data using three methods, the NRMS and Predictability (Pred) measures of Kragh and Christie (2002) and the signal-to-distortion ratio (SDR) method of Cantillo (2011). Because time-lapse noise was comparable to the observed change, multiple methods were used to analyze data reliability.

The reflections from the top and base reservoir were identified on the corridor stacks by correlation with a synthetic response generated from the well logs. A consistent change in the corridor stack amplitudes from pre- to post-CO2 injection was found for both the top and base reservoir reflections on all ten shot locations analyzed. In addition to the well-log synthetic response, a finite-difference elastic wave propagation model was built based on rock/fluid properties obtained from well logs, with CO_2 induced changes guided by time-lapse crosswell seismic tomography (Ajo-Franklin, et al., 2013) acquired at the DAS site. Time-lapse seismic tomography indicated that two reservoir zones were affected by the flood. The modeling established that interpretation of the VSP trough and peak event amplitudes as reflectivity from the top and bottom of reservoir is appropriate even with possible tuning effects. Importantly, this top/base change gives confidence in an interpretation that these changes arise from within the reservoir, not from bounding lithology. The modeled time-lapse change and the observed field data change from 10 shotpoints are in agreement for both magnitude and polarity of amplitude change for top and base of reservoir. Therefore, we conclude the stored CO2 has been successfully detected and, furthermore, the observed seismic reflection change can be applied to Cranfield’s 4D surface seismic for spatially delineating the CO_2/brine interface.

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Keywords: VSP, Monitoring, CO2,

1. Introduction

Indicate references by [1] or [2,3] in the text.

Time-lapse (TL) Offset Vertical Seismic Profiles (OVSP) have been shown useful in monitoring CO_2 storage (e.g. Cheng, et al., 2009, Daley, et al., 2008). TL OVSP data were acquired at Cranfield, near Natchez, Mississippi, as part of a detailed area study (DAS) site for geologic carbon sequestration operated by the Southeast Regional Carbon Sequestration Partership (SECARB). The DAS site includes three boreholes, an injection well and two monitoring wells. The project team selected the DAS site to examine CO_2 sequestration multiphase fluid flow and pressure at the interwell scale in a brine reservoir. As of 2012, the sequestration project has stored over 3 million metric tons of CO_2. A description of the sequestration test is given in Hovorka, et al. (2011).
The 21 m thick injection zone in the lower Tuscaloosa Formation is a fluvial conglomeritic sandstone with high vertical and lateral heterogeneity located in an anticlinal four-way closure at a depth of 3,200 m at the DAS site. The Tuscaloosa Formation is oil producing up dip of the DAS site, with the oil field operated by Denbury Resources Inc. The reservoir is composed of stacked and incised channel fills and is highly heterogeneous, with flow unit average porosities of 25 percent and permeability averaging 50 milliDarcy (mD) and ranging up to a Darcy (D).

The TL OVSP was part of an integrated monitoring program that included well logs, crosswell seismic, electrical resistance tomography and 4D surface seismic. The goals of the OVSP were to detect the CO_2 induced change in seismic response, give information about the spatial distribution of CO_2 near the injection well and to help tie the high-resolution borehole monitoring to the 4D surface data. In particular, delineating the CO_2/brine boundary within the Tuscaloosa is a project goal.

Data Acquisition

The VSP data were acquired in well CFU 31-F1, which is the ~3200 m deep CO_2 injection well at the DAS site. A preinjection survey was recorded in late 2009 with injection beginning in December 2009, and a post injection survey was conducted in Nov 2010 following injection of about 250 kT of CO_2. The sensor array for both surveys was a 50-level, 3-component, Sercel MaxiWave system with 15 m (49 ft) spacing between levels. The source for both surveys was an accelerated weight drop, with different source trucks used for the two surveys. Multiple complications with site access and equipment limited the number of shot points recorded and repeated, as compared to presurvey plans. Ten individual shotpoints were chosen for time-lapse analysis, all along an approximately east-west access road (Figure 1). At least two sensor array locations were recorded for each of the shotpoints used in analysis giving about 96 sensor depths for each shotpoint (allowing for some bad sensors in each survey). Source locations were surveyed with GPS for relocation.

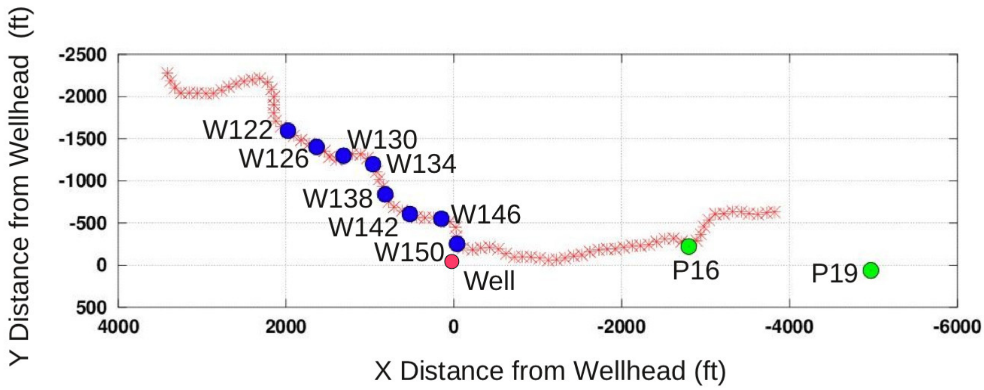


Figure 1: Shot point locations utilized for OVSP analysis (blue and green dots) along with injection/VSP well location (red dot). Red line is access road.

Time-Lapse Difference and Repeatability

Following standard editing, stacking, wavefield separation, spherical divergence correction and downgoing-wave based deconvolution, a depth error analysis showed multiple disagreements of tool depths and one-way travel times between the two surveys. Initial processing had used a reference horizon to normalize both amplitude and travel time at a depth above the reservoir, where only near-surface weathering layer changes were expected. However, the depth errors, and associated travel time uncertainty, led to application of a time shift to 'flatten' the data to an arbitrary time for calculation of corridor stacks, and the decision to focus on amplitude change (not time shifts). Corridor stacks were used to maximize signal-to-noise ratio (S/N) for each shot point but imaging spatial variation in reflectivity was not attempted due to the relatively poor S/N. Figure 2 shows an example shotpoint (W134) data set, with pre and post injection upgoing reflection data, and their difference, along with a corridor stack for pre, post and difference.

The difference data from all shotpoints were found to have residual amplitude difference at many depths, including the reservoir. We examined the overall time-lapse repeatability of the OVSP data using three methods, the NRMS and Predictability (Pred) measures of Kragh and Christie (2002) and the signal-to-distortion ratio (SDR) method of

Cantillo (2011). While NRMS is a widely used measure and good for comparison, the Pred and SDR calculations are not sensitive to uniform time shifts since they are normalized cross correlation measures. Pred and SDR remain sensitive to time-varying time shifts. The results of this repeatability analysis are shown in Figure 3. In general the repeatability is poor, which limited our confidence in the interpretation of CO_2 induced changes in reservoir reflectivity. Furthermore, the thin reservoir (~21 m) is near the tuning regime. To better understand the observed reflectivity change and tuning effects, we conducted a modeling study using time-lapse velocity changes measured at field scale by crosswell seismic tomography.

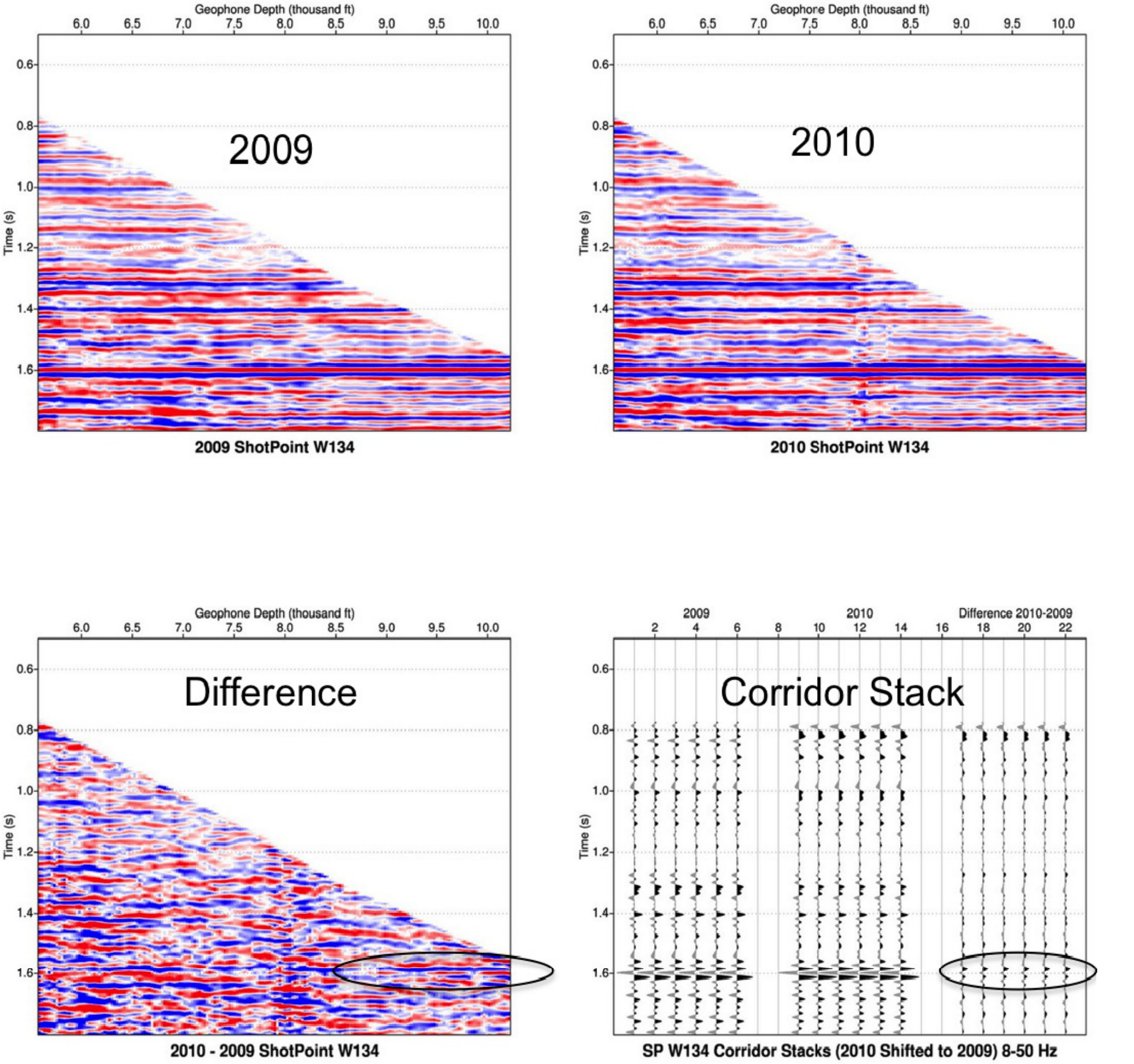


Figure 2: TL OVSP data from shotpoint W134 with arbitrary time alignment. Upgoing reflection data from 2009 and 2010 (top, left and right) is shown, along with the difference (lower left) and corridor stacks of the three data sets (lower right). Injection zone is indicated with black circle. Each plot is independently normalized, with corridor stacks having true relative amplitude.

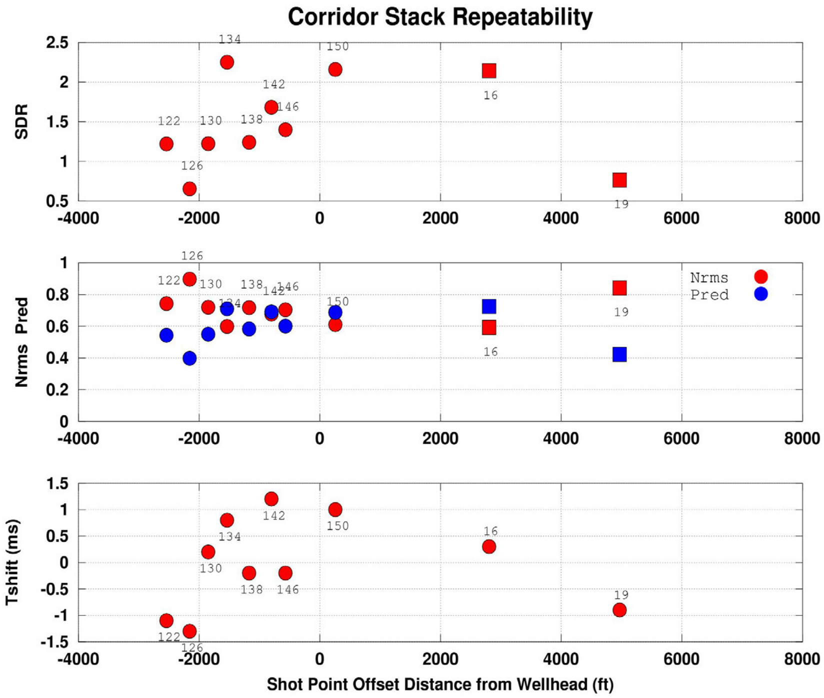


Figure 3: Repeatability analysis of corridor stack at each shot point using SDR method (top), NRMS and predicatability (middle) and the time shift indicated from SDR analysis (bottom)

Well Log Synthetic and Finite Difference Modeling

Modeling requires pre and post flood velocities and densities. No dependable post flood sonic logs or pre flood shear logs were available from the TL OVSP well (CFU 31F 1). Pre flood compressional velocity and density were taken directly from CFU 31 F1 logs. A uniform Vp/Vs ratio of 2.0 was adopted based on shear logs from nearby wells.

Estimates of post flood compressional velocities were based on crosswell seismic tomography (Ajo-Franklin, et al., 2013) acquired at the DAS site. Tomography indicated that two reservoir zones (Z1 and Z2 in Figure 4) were affected by the flood. Using the largest velocity changes indicated in the tomography, velocity of the Z1 zone was lowered by 300 m/s, with the Z2 zone lowered by 250 m/s. The CFU 31 F1 logs were then lowered by these amounts over the two zones to yield the post flood velocities as shown in Figure 4. Post flood density reduction of 10% was used in both zones based on estimates of porosities and CO2 density. These maximal changes of velocity and density were adopted to show the magnitude of the expected response, and probably overestimate the actual changes in portions of the reservoir.

A 3D isotropic staggered grid finite difference (FD) algorithm (Levander, 1988; Graves, 1996) was used to simulate the response of the TL OVSP through the 1D pre and post models developed from the well logs and tomography. A grid spacing of 2 m and time step of 0.0001 s was used to calculate 3 s of synthetics. The well log scale models of Figure 4 were first Backus averaged (Backus, 1962) over the grid spacing interval, and then further smoothed over a 6 m radius. Synthetic traces from each simulated offset were then processed using the same flow as the field data. Results are shown in Figure 5.

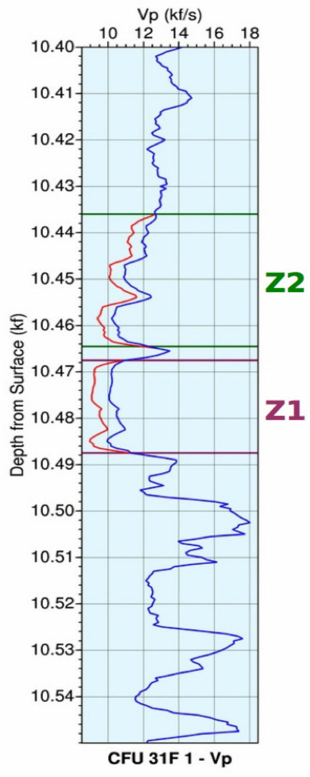


Figure 4: Pre injection P-wave log used for modeling (blue) with post injection velocity in two reservoir zones (Z1 and Z2) taken from time-lapse crosswell tomography (red).

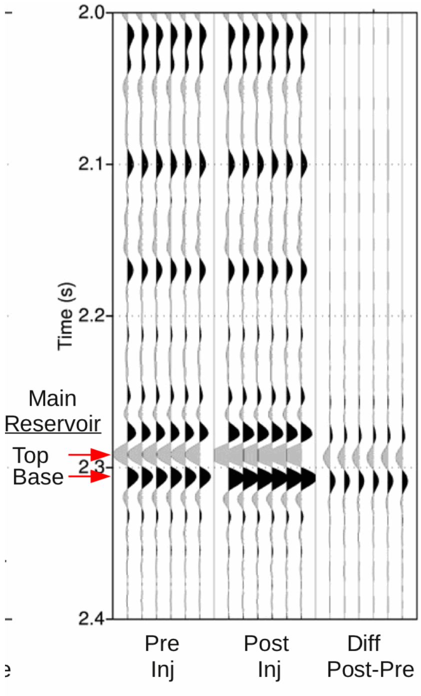
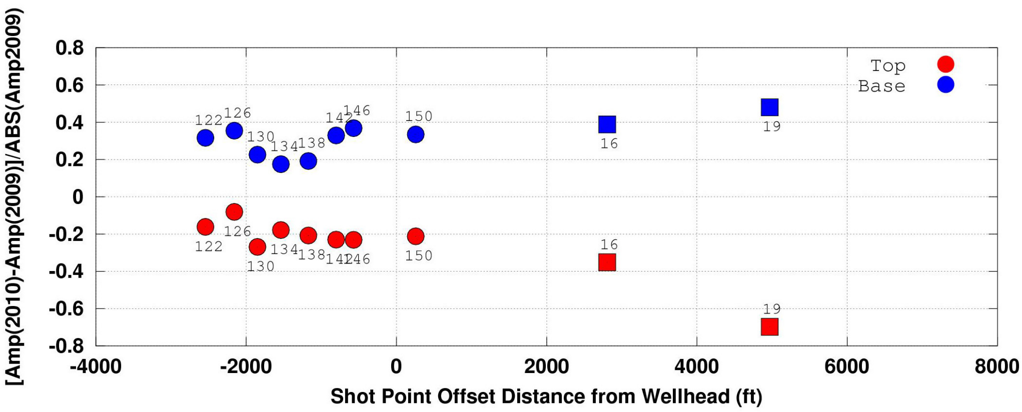


Figure 5: Corridor stacks from FD modeling of pre and post injection models (left and center) with difference (right). The events associated with the top and base of the reservoir are indicated with arrows.

Additionally, well log synthetics with Backus averaging were obtained with pre and post injection models. Zoeppritz reflectivity (using FD model and estimated incident angles) was calculated.

Figure 6 shows a comparison between the FD results, Zoeppritz equation calculations, and field data corridor stack amplitudes from top and bottom reservoir for pre and post injection. The synthetic results show an increase in amplitude difference for the base of reservoir and a decrease in amplitude difference for the top of reservoir, in agreement with the field data results. The size of the differences for the synthetics and field data are also of the same order of magnitude. This suggests that the differences seen in the field data are related to CO2 displacing brine.



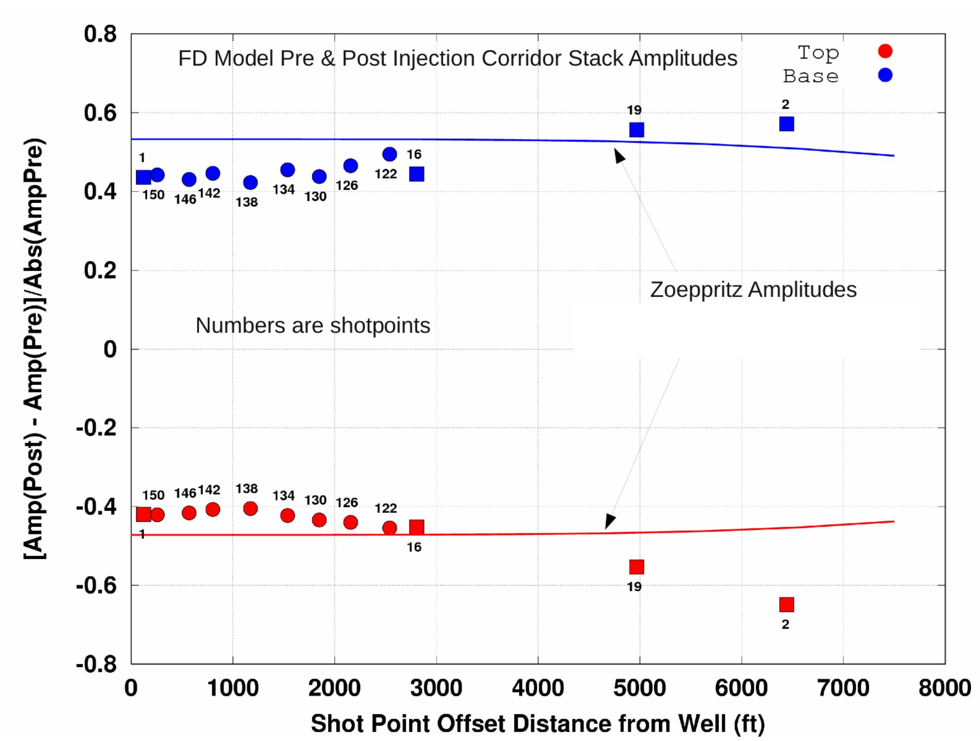


Figure 6: Time-lapse change in reflection amplitude for field data (top) and FD modeling (bottom) with Zoeppritz calculation shown as solid lines on model plot. Top (red) and base (blue) reflection change shown for each offset shot point (SP number labeled for each point). Modeling result in absolute value of offset distance.

The difference between the Zoeppritz and FD amplitudes, particularly at near zero offset, is of concern. At this point, it is not understood. Simpler models do not show these differences. This discrepancy may be related to the smoothing applied for the FD simulation. The validity of using the staggered grid FD scheme to model discrete interfaces has been a topic of wide discussion (Moczo, et al, 2002). Backus (Backus, 1962) like harmonic averaging has been suggested as a justified approach (Graves, 1996).

Seismic modeling was undertaken to address two questions. First, with an injection zone thickness of 21 m, the target zone is near the tuning regime for seismic frequencies. Modeling established that the interpretation of the trough and peak event amplitudes as reflectivity from the top and bottom of reservoir is appropriate even with possible tuning effects. Second, the time-lapse reflectivity differences between the top and bottom of the reservoir seen in the data are of the same order of magnitude as those predicted by the modeling.

Conclusions

A TL OVSP data set recorded at the Cranfield DAS site and hampered by acquisition problems does show changes in reservoir reflectivity associated with CO_2 displacing brine. Corridor stacks were used to maximize S/N but imaging spatial variation in reflectivity was not attempted due to the relatively poor S/N. Calculation of TL repeatability, using multiple methods, indicated the need for corroborating information to interpret observed amplitude changes. Seismic modeling established the interpretation of the trough and peak event amplitudes as reflectivity from the top and bottom of reservoir. In field data a consistent change was seen at each shot point in both top and base reservoir reflectivity. Importantly, this top/base change gives confidence in an interpretation that these changes arise from within the reservoir, not from bounding lithology. Further, the magnitudes of these changes are in agreement with those predicted by modeling. This analysis of top and base amplitude change can be applied to Cranfield's 4D surface seismic for delineating the CO_2/brine interface.

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