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Seismic reflection data processing of 3D surveys over an EOR CO_2 injection.

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Abstract

In this project three 3-D reflection seismic surveys were analyzed with respect to pre and post stack reflection processing steps that resulted in the identification of a possible pre-stack seismic attribute proxy for subsurface supercritical CO_2. The project was part of the Bureau of Economic Geology collaboration with the National Energy Technology Laboratory of the United States Department of Energy and the Bureau of Economic Geology as part of a Southwest Regional CO_2 Sequestration Partnership. A variety of processing techniques were used to calculate seismic attributes and invert the seismic post stack seismic data to determine acoustic impedance. Methodologies for acoustic impedance inversion included Model-based inversion, bandwidth limited inversion, colored inversion, sparse spike, and neural network. In addition, pre-stack amplitude variation with offset (AVO) analysis was completed using second order polynomial, third order polynomial, Shuey 2-term, Shuey 3-term, linear, Verm-Hilterman, Aki-Richards 2-term and Aki-Richards 3-term methods. Using a combination of Shuey 3-term coefficients we believe that we have identified a useful proxy for monitoring subsurface CO_2. In our analysis the attribute anomaly variation proxy is spatially located above brine fluid, flat bottomed and appears to be pore-phase variation. It follows reasonable trapping geometries and appears to be linked with possible earlier CO_2 injection sites.

Keywords: Carbon Sequestration; Rock Physics; Pore Scale Properties; CT Characterization; ImageJ; 4D Seismic; SEM Image Analysis; AVO

Introduction

The U.S. has a rich history of productively using CO_2 for increasing oil recovery. Large-scale CO_2 floods were started in the 1970s and 1980s, including at famous oil fields such as SACROC, Seminole and Wasson, in the Permian Basin of West Texas. The first of these large-scale CO_2-EOR (Enhanced Oil Recovery) projects, at SACROC, transported and used industrial CO_2 captured from a series of natural gas separation plants. Today, over 40 million metric tons of CO_2 is purchased and injected for oil recovery in the U.S., with about 10 million of these

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tons from industrial sources. Importantly, because of recycling, essentially all of the CO_2 injected to date still remains in the oil reservoir.

The goal of this study was a detailed 4D reflection seismic imaging project focused on a Phase II validation injection site. This project was a collaborative effort with the Southwest CO2 Sequestration Partnership and part of the national Regional Carbon Sequestration Partnerships (RCSPs) effort to help develop the technology and methodology relevant to CO_2 sequestration in different regions and geologic formations.

Method

We collected two 3D reflection seismic surveys over an active CO_2 injector, which was part of a five spot EOR pattern. In addition, we had access to a small region of a previously collected 3D survey in the immediate region of the injector.

We designed a swath type geometry centered the injector with the swath. Forward modeling predicted high-fold in the target region for our expected subsurface structure. In total five geophone lines were used with brick type shooting pattern. The correlated record length was 6 seconds and the energy source consisted of two 22,000 kg vibroseis trucks. Data was collected by LoneStar LLC. Before the first swath survey noise tests were conducted using the following parameters:

Number of sweeps
4/6 sweeps
Sweep frequency range
8-96 Hz, 8-128 Hz, Variable frequency per sweep
Sweep length
6/8/12 seconds
Sweep rate
Linear, 3 dB/octave, Variable sweep
Ground force phase lock (generally <5-8 deg)

Field recording parameters were then set to a sweep rate of 3 dB/oct with boost, sweep length of 8 seconds, and at each energy point 6 sweeps of 8 – 116, 10 – 120, 12 – 122, 14 – 124, 16 – 126, and 18 – 126 Hz were recorded.

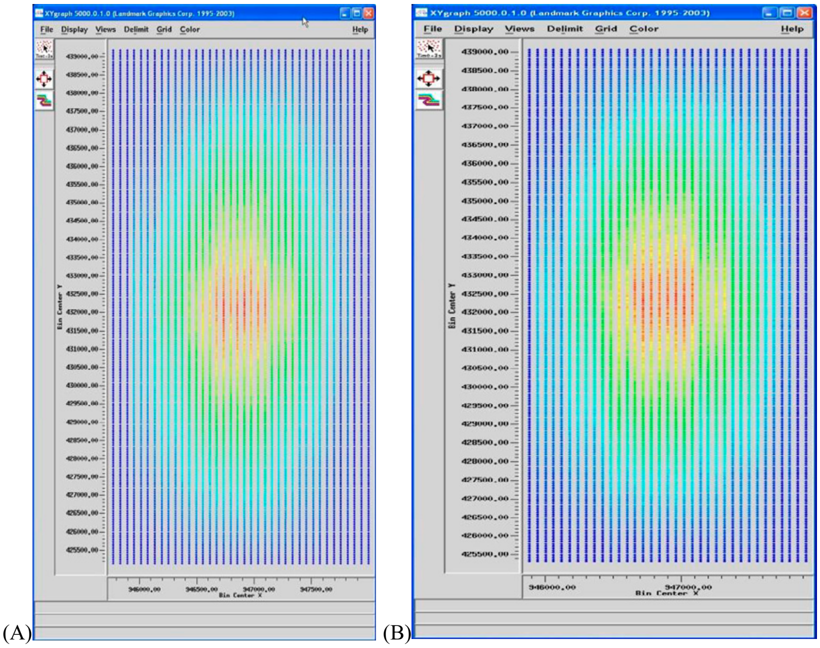


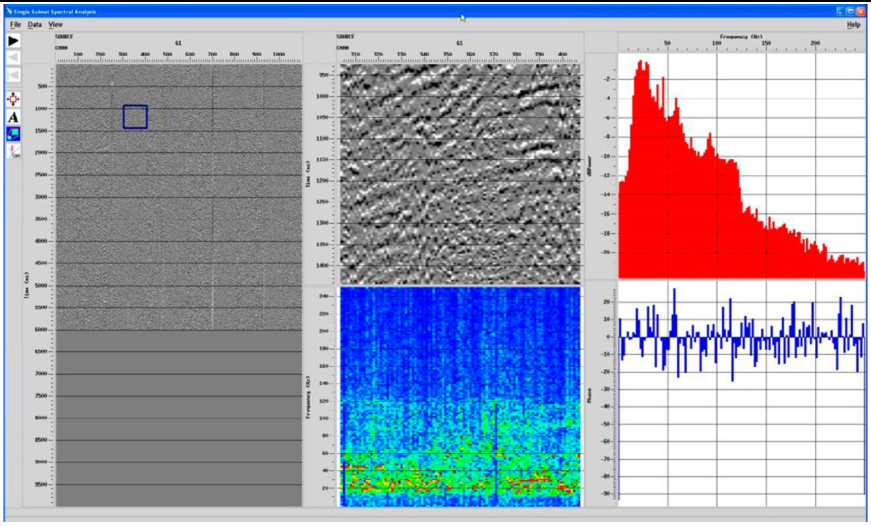
Figure 1: CDP Fold for the (A) first and (B) second surveys. Maximum fold was 90-120 in the target region.

Data was of high quality and recorded at 2 ms time sample spacing. Figure 1 shows the high and consistent fold in the target region near the injector. Our swath geometry was designed to minimize acquisition cost while maintaining high fold over the target horizon region. The target region was at an approximately depth of 6600’ below surface and consisted of a Paleozoic carbonate feature.

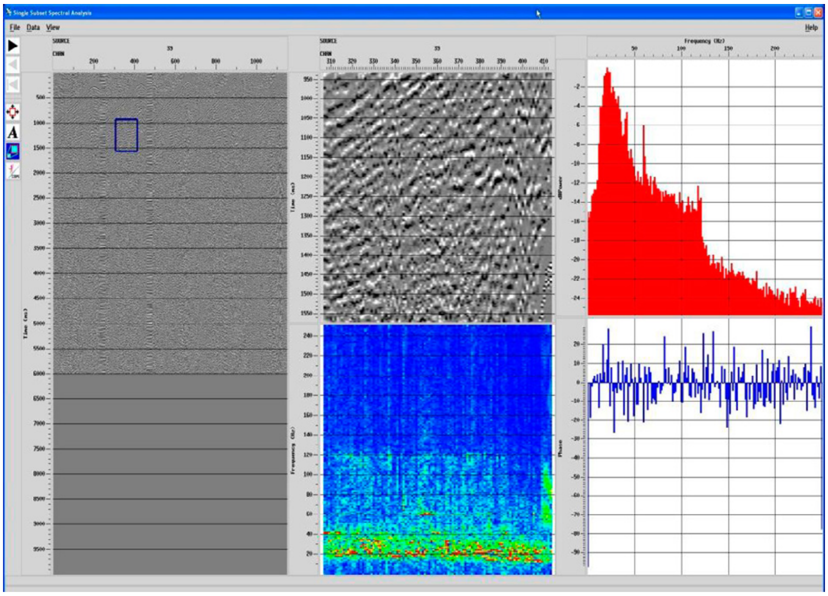
Figure 2 shows a spectral analysis comparison of two shot records from the region of interest. We were pleased by the consistent nature of these characteristics. In almost all cases geophones were planted in exactly the same coordinates between the two surveys. The majority of energy points were also collected in the same spatial locations as determined by differentially corrected global positioning satellite (GPS) measurements.

Three dimensional reflection seismic data was reprocessed to determine both pre-stack and post-stack seismic attributes as part of this study. Potentially, seismic attributes allow fine detail to be determined from reflection seismic data that can be interpreted to correspond to subsurface variation in framework and pore filling phase variation (Castagna and Buckus, [1]; Hilterman, [2]);. We found that there was a correspondence between variation of the calculated Shuey 3-pre stack seismic attribute (Shuey, [3]) and potential sites for accumulation of supercritical CO_2 from previous injections at this site.

At the target zone the pre-stack migrated gathers showed amplitude variation with offset (AVO) behavior which was consistent and unique to this reflector region. Figure 3 shows a representative series of gathers, Figure 4 shows the more detailed coefficient behavior for a single CDP gather.



(A) Spectral analysis of the region of interest in the first swath survey record with respect to the CO_2 injection.



(B) Spectral analysis of the region of interest in the second swath survey record with respect to the CO_2 injection.

Figure 2: Comparison of the (A) first and (B) second swath surveys in the region of interest. Note the consistent time and frequency characteristics of these two shot records. To aid in pre-processing trace quality control for each survey we calculated:TRCAMP: Average Trace Energy, FB_AMP: Average First Break Energy, PFBAMP: Average Pre-First Break Energy, PFBFRQ: Average Pre-First Break Frequency, SPIKES: Spikiness FRQ_PK: Dominant Frequency of Data, FRQ_DV: Statistical Frequency Deviation, ADECAY: Estimated Trace Energy Decay rate in dB.

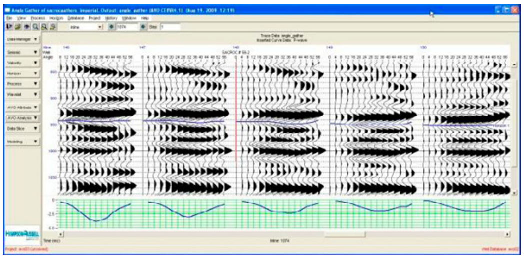
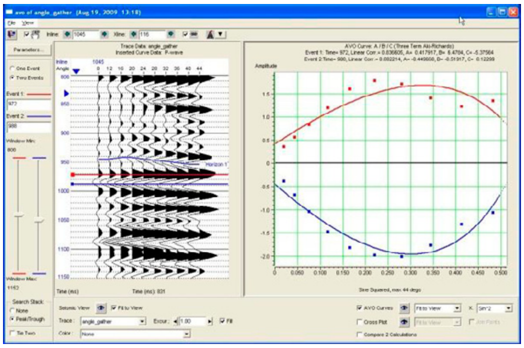


Figure 3: AVO characteristics of the target horizon. Note the consistent behavior of the variation of amplitude with offset in these CMP gathers. .



AVO Curve: A / B / C (Three Term Aki-Richards)
Event 1: Time= 972, Linear Corr = 0.836605, A= 0.417917, B= 6.4794, C= -5.37564

Figure 4: Aki and Richards (1980) 3 term coefficient behavior for two reflectors in target region. The derived statistical measurements of the A, B and C terms accurately represent the amplitude variation with offset behavior of this gather, which is representative of our highest quality data.

AVO

Before undertaking our seismic analysis, we wanted to model how CO_2 replacing brine would change the AVO response of our reservoir. For this we used the CREWES Zoeppritz Explorer, which solves for the exact solution of the Zoeppritz Equations. The Zoeppritz equations model the reflection and transmission coefficients as a function of offset angle at a boundary, and can be used to infer properties of the pore filling phase [7].

We used our laboratory measurements as the input values for lower layer, and values taken from our reference shale for the top layer. The difference between brine filled and CO_2 filled phases is noticeable: The Intercept (A) for the brine filled example is positive, whereas when CO_2 is substituted, (A) becomes slightly negative, and the critical angle for the CO_2 saturated example is at a larger angle than it is for brine (~73° vs. ~56°).

We then computed the AVO response around our survey region using approximately 21,000 separate points on a picked horizon of the top of the limestone reef. When these points are cross-plotted with A vs. B, the overall AVO response around the injector well is that of a Type III anomaly. Using these AVO coefficients, we examined different combinations for a signal around an injector well that might indicate the presence of a CO_2 flood. When we look at the the AVO response of individual gathers in the area of the injector well, we see that the Intercept A is negative, but far away A becomes positive. This agrees well with our Zoeppritz calculations for CO_2 saturated rock. After examining different combinations of coefficents, we determined that for our limestone reservoir, a high value for ½(A+B) using the Shuey 3 Term approximation is an excellent indicator for CO_2 (See Figure 6)[5]. For the Shuey 3 Term approximation, the attribute ½ (A+B) is an estimate of Rp-Rs (P Reflectivity-S Reflectivity) [8].

We created a Prestack Attribute Volume of Shuey 3 Term ½(A+B) over our horizon, and took time slices at 0.908, 0.920 and 0.944 seconds. In addition, a cross section near an injector well was created. From these time slices, large anomalies can be seen in the 0.944s time slice directly around the injector well, with another anomaly occuring in the 0.908 and 0.920 time slices. This upper anomaly follows the dome shaped structure of the reef, as can be seen in the cross section (Figure 5). This upper anomaly most likely corresponds to an older injection of CO_2, as it had time to migrate up to the sealing unit on top of the reef.

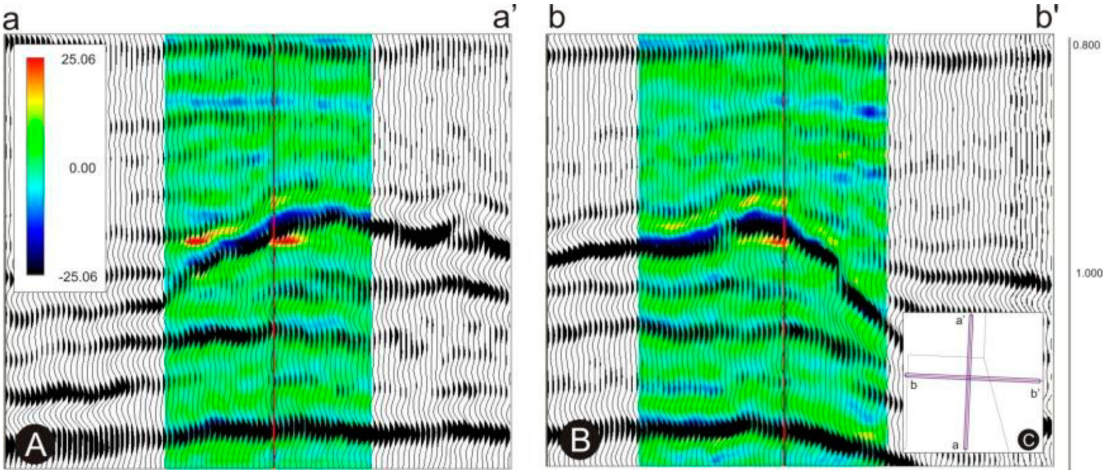


Figure 5: Two reflection seismic lines are shown with the 1/2(A+B) Shuey 3 term superimposed, the ties are shown as vertical red lines in the center of subfigures A and B. We interpret high values to represent a possible proxy for subsurface supercritical CO2. A) North-south line, b) East-west line, C) Reference map. The lines are approximately 1800 meters in length.

In summary, after examining different combinations of AVO coefficents, we determined that for this limestone reservoir, a high value for ½(A+B) using the Shuey 3 Term approximation is an excellent indicator for CO_2 (See Figure 5). Details related to Figure 5 are presented in Purcell et al., [5] and [6]. Such a proxy could be useful in mapping the extent of supercritical CO_2 saturation associated with enhanced oil recovery operations. The swath surveys also shows differences in reflector amplitudes in the target regions.

Conclusions

After completion and analysis of an AVO study over our survey area, we found that areas near our injector wells showed an AVO. The best results were obtained by using ½(A+B), where A is the intercept and B is the slope. It is believed that a large value for ½ (A+B) indicates the presence of supercritical CO_2 due to the strong positive values near an injector well. Our Swath survey 1 and Swath survey 2 3D surveys in the SACROC field have been completed. The data quality of both surveys looks excellent and consistent. These results should allow 4D calculation of seismic attributes and change detection related to the CO_2 injection. This technique has the advantage of being repeated as many times as needed, and is able to track sequestered CO_2 over a large area. This technique can be combined with other methods, such as surface monitoring, VSP, isotope based geochemical monitoring of water, electromagnetics and other methods to most effectively monitor sequestered carbon dioxide in order to minimize any potential impacts to the shallow subsurface from deep CO_2 injection.

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Acknowledgments

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