Pre- and Post-injection Vertical Seismic Profiling over the Southwest Regional Partnership’s Phase II Fruitland Coal CO2 Pilot

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Abstract

In this study we report on the results of pre and post injection vertical seismic profiles collected at the Southwest Regional Partnership (SWP) on Carbon Sequestration’s San Juan Basin Fruitland Coal pilot test. The project is funded by the U.S. Department of Energy and is managed by the National Energy Technology Laboratory. The pilot test was undertaken in collaboration with ConocoPhillips as a joint enhanced coalbed methane recovery test and demonstration of CO₂ sequestration in deep, unmineable coal seams. The SWP conducted the pilot in the Upper Cretaceous High Rate Fruitland production fairway southwest of the northwest trending basin hinge. CO₂ injection began July 30th of 2008 and continued through August 14th of 2009. During the 12 month injection period approximately 319 MMCF, equivalent to nearly 18,407 short tons of CO₂ were injected into the Fruitland coals.

The pre-injection vertical seismic profiles were completed on June 2nd and 3rd of 2008. The post injection surveys were acquired on September 17th, 2009: a month after CO₂ injection was completed. The monitor VSPs were not run until the reservoir was pressured down. Both pre- and post-injection surveys included a zero offset VSP and three offset VSPs. The zero offset source was located 114 feet from the injection well. Long offset sources were located 1498 feet from the injection well along a 216° azimuth, 1693 feet along a 34° azimuth, and 1942 feet along an azimuth of 349°.

Elemental analysis through the lower Fruitland reveals thick coal seams in the intervals 2950' to 2970' subsurface, 2975' to 2986', 3048' to 3060' and 3111' to 3336'. Compression and shear wave velocities were measured using the Sonic Scanner from 285 feet to 3132 feet subsurface. Density is also available from the Platform Express log suite. Synthetic seismograms are used to tie subsurface geology to surface 3D seismic in the area and the VSP responses. Results from time lapse processing are preliminary. The WVU funded processing effort through Schlumberger continues.

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Background on the study

The study discussed in this poster was funded through a West Virginia University/National Energy Technology Laboratory (NETL) contract. During the SWP’s Phase II effort at the site, West Virginia University undertook several site characterization activities over the San Juan Basin pilot in support of NETL Monitoring, Verification and Accounting (MVA) team efforts. These activities were primarily intended to help locate possible CO₂ leakage pathways and identify additional locations to place monitors for PFC tracer and soil gas anomalies. The integrated studies were designed to help optimize estimation of CO₂ escape volume if leakage were to occur. Collaborative efforts were also designed to complement and enhance the ongoing efforts of the Southwest Regional Partnership (SWP).
Site characterization activities included field and satellite based fracture mapping, subsurface mapping of the region using geophysical logs, evaluation of interferometric synthetic aperture radar (InSAR) observations to accurately measure ground movements at the site, detailed electromagnetic surveys, lineament analysis of radar and Landsat imagery and 3D seismic interpretation (see locations in Figures 1 and 2). Additional discussion of these efforts can be found in Wilson et al. (2008 and 2009).

In support of the present study WVU and NETL initiated and funded logging operations of the ConocoPhillips EPNG COM A ING 1 injection well, helped plan and design the VSP time-lapse surveys and set up a separate contract with Schlumberger to fund additional time-lapse processing of the VSP data.

Initial time lapse processing was completed in November of 2009. Significant differences in the acoustic properties of the Fruitland sequence attributable to CO2 injection have not been detected. Additional time-lapse processing is still underway.

**Figure 1:** Three offset VSPs and one zero offset VSP were collected at the site to provide baseline and monitor (post-injection views of the site). The source point locations are shown on the QuickBird image (green squares).
Presence of archaeologically sensitive areas at the site limited our choice of offsets. The QuickBird image (Figure 1) also shows locations of producing wells, NETL tracer and soil gas sample points and tiltmeters. The baseline VSP surveys were completed about two months prior to CO2 injection. The monitor VSPs were surveyed 1.3 years later, just over a month following the completion of CO2 injection.

Figure 2: a) Regional location map and b) structure on the basis of the Fruitland coal

Figure 3: Routine wiggly trace variable area display of a 3D line from the San Juan basin pilot 3D.
Figure 4: Post-stack processed view of migrated stack line (Figure 3) reveals potential faults and fracture zones within the Fruitland Formation and Kirtland Shale. The VSP was run in the center COM A ING 1 well.

Figure 5: Sensors for the VSP survey were placed in the ConocoPhillips EPNG COM A ING1 CO2 injection well (A). The relative locations of the source points A-D are shown along with surrounding production wells in B. The Fruitland sequence is highlighted in a seismic line from the 3D survey (C). The internal reflection response is complex and reflection discontinuity common. An isopach of the Fruitland sequence (D) reveals considerable variation in travel time through the Fruitland reservoir interval.
Acquisition and Processing Comments

The baseline and monitor VSP surveys (Figure 6) were collected using a 12 second duration Vibroseis upsweep from 8-120 Hz. Differences between baseline and monitor surveys often arise for a variety of reasons. In the present case, for example, heavy rains preceded the monitor survey while the initial baseline survey was conducted under dry conditions. Other differences between the baseline and monitor survey unrelated to CO2 injection include repositioning of the source at offset B (see Figure 5) to reduce distortion levels during the monitor survey, skipped shots during the baseline survey and differences in receiver depths in the recording well noted in the monitor survey. Offset VSP processing steps included true amplitude recovery, bandpass filtering (3 – 120 Hz.), amplitude normalization, median velocity filtering to separate downgoing and upgoing wavefields and waveshape deconvolution. Processing of the baseline and monitor data sets were identical. The differenced data sets (monitor – baseline) retain considerable amplitude at all recording times but the differences are especially noticeable for Offset D (Figure 5, see panel 2 right). Additional processing included crossequilization (e.g. Ross et al., 1996) and non-rigid matching (Nickel and Sonneland, 1999). Refinements to the VSP processing workflow continue to be tested.

Figure 6: Comparisons of the baseline (pre-injection) VSPs to bandpass filtered arbitrary lines extracted from 3D seismic that extend through the injection well and VSP source points (B, C and D) (see line location map Figure 5). The VSP data were collected for the Southwest Regional Partnership and processed by Schlumberger. (VSP displays, courtesy of Schlumberger, 2008).
Source offsets B and C (Figure 6) lie along a northeast-southwest line (~N30E). Some relative time-shift between the 3D seismic and offset VSP event times was introduced to align interpreted event correlations and arrival times. Common midpoint locations in the VSP displays increase in offset from right to left for Offset B and from left to right for offsets C and D (see Figure 5B). Midpoints extend at most to approximately half the distance between the injection well in which the geophones were placed and individual source point locations.

**Time lapse comparison of monitor and baseline surveys**

CMP differences (Run 2- Run 1 or monitor – baseline) are shown for offset VSPs B, C and D (Figure 7). These represent output from the initial stage of processing. Significant amplitude response is observed throughout the differenced records. The differences are more noticeable for Offset D, particularly for the Fruitland and deeper events. The synthetic response (Figure 9C) indicates arrival times of approximately 0.55 seconds for the upper Fruitland.

Additional processing incorporated migration and conversion to depth along with cross-qualization and non-rigid matching (Figure 8). Cross-qualization is defined by Ross et al. (1996) as a combination of matched filtering, amplitude scaling and static correction that produces a match between the baseline and monitor responses. The process is usually designed on data above the zone of interest in portions of the data unlikely to have been affected by production or injection. When applied in this fashion, the process eliminates significant difference in areas above the reservoir. Differences remaining within the reservoir and below can then be interpreted to result from possible change of acoustic properties of the reservoir. Non-rigid matching (Nickel and Sonneland, 1999) is another approach with similar objective. This process is also generally designed on data above the reservoir. It assumes that samples (voxels) in the monitor survey are displaced versions of those in the initial survey. Samples in the monitor data set are relocated to improve the match and the relocated data form a reference survey that is subtracted from the baseline survey to provide a time-lapse view in which differences may be restricted to reservoir effects.

Results presented for cross-qualization and non-rigid matching (Figure 8) were designed on the entire data set. This represents a global design approach. Global design, in this case, effectively removed any indications of change attributable to differences of acoustic properties in the reservoir and deeper intervals for offsets B and D. Differences observed in Offset C are difficult to interpret. A band of relatively high amplitude differences is observed around depths of 2700 feet (approximately 250 feet above the upper Fruitland Coal) and in depths beneath the reservoir (>3200 feet). The differences show no clear relationship to changes of acoustic properties within the reservoir.

Figure 7: Monitor minus baseline surveys for source positions B-C.
What could we expect to see in the time-lapse VSP response?

Some published studies suggest that acoustic impedance of coal will be increased by CO2 injection due to preferential adsorption CO2 molecules and coal swelling. Xue and Ohsumi (2005), for example, make detailed measurements of swelling strain and waveform traveltime changes for the Kushiro Coal in Hokkaido, Japan. They note a 10% increase in P-wave velocity at 2.5 MPa (~362 psi) and perhaps up to 12.7% at 12 MPa (supercritical). Nishimoto et al. (2008) report only 2.2% increase in Vp at 12 MPa under supercritical conditions.

McCrank (2009) notes that CO2 injection into the Ardley Coal, Alberta, produces a 10% reduction in velocity attributed to increased coal plasticity after a 9 month CO2 soak.

In the following section (see figures 9 through ) we calculate AVO variations in CMP gathers using full solutions of the Zoepritz equations. CMP gathers in this case are used as a proxy for the VSP response. In the gathers, short to long offsets correspond roughly to upper to lower borehole sensor locations. Two possible scenarios are modeled: 1) CO2 injection reduces coal velocity and 2) CO2 injection increases coal velocity. The results suggest that in both cases significant time lapse response occurs due to relative delay or advance in the pre-to-post injection traveltimes. The accompanying model studies evaluate potential AVO and time lapse response to CO2 injection; present simulations for alternative cases in which CO2 increases and decreases coal zone velocity; and, determine the potential for time lapse AVO observations in CMP and VSP records.
Figure 9: Zero offset VSP used as TD curve to adjust sonic and density travel time data used to generate AVO synthetics.

Figure 10: Original and modified logs for the fast model.
Comparisons of synthetic baseline and monitor CMP gathers (Figure 7) showing time lapse responses for two cases: 1) increased velocity in the coal section and 2) decreased velocity within individual seams. Close up views of the Fruitland coal section highlight differences observed for each case. AVO plots are presented for both cases. The CMP gathers are used as a proxy for the VSP response: the response at longer CMP offsets corresponds to deeper phones in the borehole VSP. For either case the time lapse response results primarily from relative traveltime delay or advance.

Figure 11: Synthetic AVO response computed for the fast case.
Figure 12: Time lapse responses for two cases: 1) increased velocity in the coal section and 2) decreased velocity within individual seams
Comparisons of synthetic baseline and monitor CMP gathers (Figure 12) showing time lapse responses for two cases: 1) increased velocity in the coal section and 2) decreased velocity within individual seams. Close up views of the Fruitland coal section highlight differences observed for each case. AVO plots are presented for both cases. The CMP gathers are used as a proxy for the VSP response: the response at longer CMP offsets corresponds to deeper phones in the borehole VSP. For either case the time lapse response results primarily from relative traveltine delay or advance.

Conclusions
At present, results of time-lapse processing suggest that differences between the monitor and baseline surveys are minimal and do not reveal any significant change in the acoustic properties of the reservoir during the 1.3 year interval between the two surveys.

Although injection proceeded for 1 year with total injection volume of 319MMCF, the injection well was allowed to pressure down for one month preceding the VSP monitor survey. The diffusion of CO2 into the surrounding area during the pressure down period may have significantly reduced the impact of residual CO2 on the acoustic properties of the reservoir. The reasonable expectation under these circumstances is that significant differences in the acoustic properties of the reservoir were likely to be minimal and perhaps unobservable.

Also, as noted earlier, the crossequalization and non-rigid matching processes presented here incorporated a global design approach which tends to eliminate all differences between the baseline and monitor data sets. At present, we await results in which the crossequalization and non-rigid matching operations are designed on data from above the reservoir. There are inherent errors in either the global or local design approach. The potential for success using local design in the window of data above the reservoir is limited due to a lack of good signal-to-noise ratio and a lack of coherent reflection events in the window of data overlying the Fruitland. The results of reprocessing may continue to suggest that CO2 induced change is not observable. This outcome would most likely be due to extensive pressure draw-down following injection.

In this study, we also modeled differences we might expect to see from CO2 injection. Time lapse differences in two CMP attributes were evaluated: 1) AVO, and 2) travel time delay or advance. Travel time delay or advance is a discriminating attribute whereas the difference in AVO is not. The simulations suggest that differentiation between faster or slower effect may be detected in CMP gathers or VSP surveys through cross-equalization of the seismic response above the injection zone followed by careful analysis of travel time differences between events in the baseline and monitor surveys arising from within and beneath the injection zone.

References


Xue, Z., and Ohsumi, T., 2003, Laboratory measurements on swelling in coals caused by adsorption of carbon
dioxide and its impact on permeability of coal: Coal & Safety, no. 23, p 36-43.