Site closure monitoring of two CO2 plumes with VSP at the Frio Pilot

GCCC Digital Publication Series #10-24

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Keywords:
Field study-Frio-Liberty Co-TX, Monitoring

Cited as:
Daley, T.M. and Hovorka, S. D., 2010 Site Closure Monitoring of Two CO₂ Plumes with VSP at the Frio Pilot, American Geophysical Union, Fall Meeting 2010, abstract #H13C-0983

The Frio Pilot was an early field test of geologic sequestration of CO₂ in a brine aquifer in the US, near Houston, Texas. In 2004 about 1600 tons of CO₂ were injected into the Frio C sand at a depth of 1500 m. Among other monitoring tools, pre- and post-injection vertical seismic profiles (VSP) were acquired in 2004. In 2006 the Frio-II pilot performed an injection of about 350 tons of CO₂ into the Frio Blue sand at a depth of 1650 m. Both injections were at supercritical conditions for the CO₂ (150 and 165 bar, 53 and 60 degree C), and in steeply dipping (~16 degrees), high porosity (34%), high permeability (2.5-4 Darcy) sandstones. Despite the steep dip, both CO₂ plumes were expected to have limited migration due to residual trapping in the vicinity of the injection well. In 2009 the Frio Pilot injection well was plugged and abandoned, and the site was closed. Before closure a third VSP was acquired in the injection well. Initial processing of the first two VSP’s had shown a clear amplitude change coincident with the CO₂ in the C sand. No VSP was performed immediately after the 350 ton Frio-II injection because of uncertainty over the detectability of this small amount of CO₂. To assess the detectability of both CO₂ plumes with the 2009 site closure VSP, all three VSP's were reprocessed using identical algorithms and parameters. Initial results indicate that both plumes can be observed via reflection amplitude changes in the individual source site reflectivity. Two types of imaging were performed, VSP-CDP transform and VSP-migration, which combine multiple source points to improve spatial imaging. The multi-source imaging has less distinct amplitude changes, a result which is attributed to the small number of source points and complex velocity structure. The success of the single source point VSP analysis demonstrates VSP as a tool for site closure assurance that injected CO₂ has remained in place. Additionally, the VSP method is shown to be useful for long term monitoring of small scale CO₂ migration near a well, i.e. wellbore leakage from a deeper reservoir.

Keywords: [0915] EXPLORATION GEOPHYSICS / Downhole methods, [1699] GLOBAL CHANGE / General or miscellaneous, [1855] HYDROLOGY / Remote sensing, [7205] SEISMOLOGY / Continental crust
Abstract

The Frio Pilot was an early field test of geological sequestration of CO2 in a brine aquifer in the US, near Houston, Texas. In 2004 about 1600 tons of CO2 were injected into the Frio C sand at a depth of 1500 m. Among other monitoring tools, pre- and post-injection vertical seismic profiles (VSP) were acquired in 2004. In 2006 the Frio-B pilot performed an injection of 1500 tons of CO2 into the Frio Blue sand at a depth of 1650 m. Both injections were at supraregional conditions for the CO2, and in a steeply dipping, high porosity (34%), high permeability (2.5-4 Darcy) sandstone.

In May 2009 the Frio injection well was plugged and abandoned, and the site was capped. Before closure, a third VSP was acquired in the injection well. Despite the steep dip, both CO2 plumes were expected to have limited migration, and to show up in the VSP at the vicinity of the injection well. Initial processing of the first two VSP’s had shown a clear amplitude change coincident with the CO2 in the C sand. No VSP was performed immediately after the 350 ton Frio injection because of funding limits and uncertainty over the detection of this small amount of CO2. To assess both CO2 plumes with the 2009 site closure VSP, all three VSP’s were reprocessed using identical algorithms and parameters. Results indicate that both plumes can be observed via reflection amplitude changes from a single source location.

Two types of seismic imaging were performed, VSP-CDP transform and VSP-migration, which combine multiple source points to improve data imaging. The multi-source imaging has less distinct amplitude changes, a result which is attributed to the small number of source points and complex velocity structure which spatially distort the reflection change incorrectly. The success of the single source point VSP analysis demonstrates VSP as a cost effective tool for site closure assurance that injected CO2 has remained in place. Additionally, the VSP method is shown to be useful for long term monitoring of small scale CO2 migration near a well, which would be the situation for wellbeing leakage from a deeper reservoir.

VSP Data Acquisition

An 80 level 3-component geophone array with 7.5 m spacing was deployed in the injection well at 4 depth intervals. Geophones were clamped at depth. Explosive shots were drilled at all 6 source locations.

Reprocessing of 3 VSP Surveys

The first two Frio VSP surveys were processed and analyzed together (Daley, et al., 2008). Following the final repeat, the three surveys were reprocessed together by contractor SeismicResearch2020.

• Static shifts to shots (explosive source)
• Three component sensor rotation
• First break picking
• Downgoing deconvolution (10-100m, 600 ms)
• Wavefield separation of upgoing (11trace median filter)
• Imaging: Prestack Kirchhoff Depth Migration (PSDKM); and VSP-CDP transform

The use of these two methods requires the inversion of an accurate velocity model. This model is used for the time to depth mapping of the upgoing wavefields.

Comparison to Flow Model

The observed VSP reflection amplitude change is mapped to offset distance via seismic ray-bouncing analysis. This allows comparison to the CO2 saturation estimated from reservoir flow models. For the 2009 VSP reprocessing the reflection amplitude change was observed on the northern azimuth as a decrease on the figure (Blue sand 92 m, C sand and 137 m). These distances correspond to model saturation of ~5-10%, for the most recent calculation (6 months before VSP).

VSP Analysis

The purpose of the VSP analysis was to detect and image possible changes in the seismic response caused by the injection of CO2 in the Frio sandstone.

Drilling shot hole for explosive source

An 80 meter level 3-component geophone array with 7.5 m spacing was deployed in the injection well at 4 depth intervals. Geophones were clamped at depth. Explosive shots were drilled at all 6 source locations.

Discussion

Comparison of the above plots indicates that while limited by source points, ‘simple’ upgoing VSP processing can better detect and monitor CO2 than more advanced imaging. The current ‘state-of-the-art’ for VSP is hundreds of source points with migration used to obtain optimal spatial imaging. However, small scale CO2 acquisition plots are limited by fluid and land access, and therefore may not benefit from advanced imaging. Furthermore, these results show that small amounts of CO2 can be monitored with VSP for at least 5 years post-injection.

REFERENCES


CONCLUSIONS

• Post-injection VSP shows response from two known CO2 plumes: 1600 ton after ~5 years and 350 ton after ~3 years.
• >300 ton plume would be difficult to identify if depth was unknown, so the minimum ‘unknown’ quantity detectable with VSP at this site is ~1600 tons.
• Both plumes appear stable as predicted due to residual trapping (best detection using ‘raw’ upgoing VSP, with limited source points, the imaging methods (VSP-CDP and migration) are less clear, probably due to velocity heterogeneity and uncertainty.
• Data can be used to study repeatability, quantification, permanence, and can constrain reservoir flow modeling.

ACKNOWLEDGMENTS

The original Frio VSP work was led by the Bureau of Economic Geology at the Jackson School of Geosciences, University of Texas at Austin, supported by the GEO-SEQ project of the Carbon Sequestration project of the National Energy Technology Laboratory (NETL). The current analysis support by the National Risk Assessment Partnership (NRAP) project also at NETL, and the U.S. Department of Energy under contract DE-AC22-CH11213. Special thanks for reprocessing and imaging by Andres Chavarria and Luis LahFraite at SI2020. Overall thanks to colleagues and scientists to numerous to who have worked on the Frio Project. Upcoming processing using SEISBINS courtesy of VSPUION.

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