4-D high-resolution seismic reflection monitoring of miscible CO_2 injected into a carbonate reservoir in the Hall-Gurney Field, Russell County, Kansas

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Summary

High-resolution 4-D seismic data are providing time-lapse 3-D images of carbon dioxide (CO_2) movement through a 900 m deep 4 m thick, oomoldic limestone, Lansing-Kansas City formation oil reservoir in central Kansas. Considering the lateral and vertical variability of properties in reservoirs of this type, understanding the effects of CO_2 injection on phase behavior and gas and oil phase movement is critical to optimizing recovery and predicting long-term reservoir properties. An unconventional approach to data acquisition resulted in shot gathers with dominant frequencies above 140 Hz at 700 ms, providing a vertical bed resolution potential of around 4 m. Due to vertical permeability distribution, CO_2 injection is focused into a 2 m thick zone of this reservoir where water flood enhanced oil recovery has dropped below economic levels. By optimizing acquisition, a recording system with only 240 channels coupled with a single low power, high frequency vibrator resulted in a highly repeatable and high S/N data set at a minimal cost. Changes in reflection amplitudes on shot gathers, interpreted to be from a depth range that includes the reservoir, are due to CO_2 movement through the C zone of this reservoir. Production schemes must be developed that are dynamic and appropriate for the individual field for mature mid-continent oil reservoirs of this type to respond most efficiently to CO_2 flooding. From a sequestration perspective it is important to establish that 4-D seismic imaging can provide the necessary containment assurances for shallow storage reservoirs and at a reasonable cost. These data are beginning to help improve the understanding of fluid-flow paths, reservoir architecture, reservoir properties, and CO_2 movement for this 10-acre CO_2 miscible flood, which began in Fall 2003. Over the life of this pilot study more than 12, 3-D seismic surveys will be conducted with later data sets instrumental to determining CO_2 containment and post-injection CO_2 stability.

Introduction

This research project set out to map changes in fluid characteristics in a 10-acre miscible CO_2 flood before, during, and after the flood that began in Fall 2003 as part of the DOE-sponsored Class Revisited demonstration project. To image changes, the 4-D seismic project is utilizing twelve high-resolution 3-D compressional wave and two 2-D, 2-C shear wave seismic surveys. Unique and key to this imaging activity is the high-resolution nature of the seismic data, minimal deployment design, and the high rate and number of temporal sampling throughout the flood. The 900 m deep test reservoir is located in a central Kansas oomoldic limestone of the Lansing-Kansas City Group, deposited on a shallow marine shelf in Pennsylvanian time (Watney et al., 1995). The Lansing-Kansas City reservoir at the demonstration site is only 4 m thick with the most productive interval at the top of the reservoir being about 2 m thick, requiring dominant frequencies to exceed 140 Hz to resolve the top and bottom of the 4 m thick pay zone (Gochioco 1991; Miller et al., 1995).

This 10-acre miscible CO_2 flood involves two production wells (#12 and #13), one monitoring well (#16), two water injectors (#10 and #18), and one CO_2 injector (CO2I#1) (Dubois et al., 2001). Approximately 32 million standard cubic feet of CO_2, were injected from December 1 to March 31. The baseline 3-D survey was acquired during late November 2004 followed by two monitoring surveys each separated by six weeks (late January and late March 2004).

Background

Time-lapse 3-D (or 4-D) seismic reflection surveys have been effectively used during the last decade (Ebrom et al., 1998) to monitor conventional enhanced oil recovery (EOR) programs (Rogno et al., 1999; Gabriels et al., 1999; Lumley, 1995). Maintaining consistency and repeatability in acquisition and processing has been the most persistently identified problem associated with time-lapse seismic monitoring of reservoir production (Huang and Will, 2000; Druzhinin and MacBeth, 2001; Meunier and Huguet, 1998; Nivlet et al., 2001; Li et al., 2001). Distinguishing between changes in seismic characteristics that result from temporal variation in near-surface properties and changes occurring in reservoir intervals as a result of flooding remains a significant problem. Cross-equalization techniques have proven to be a most effective tool in reducing the impact of near-surface variations on amplitude, phase, arrival time (static), and spectral properties (Huang and Will, 2000; Druzhinin and MacBeth, 2001; Meunier and Huguet, 1998). The potential of multiple (>2 per EOR or CO_2 sequestration program) 3-D surveys to better differentiate changes in near-surface conditions from changes in reservoir fluids has not been evaluated.

Monitoring CO_2 floods in carbonate reservoirs with conventional 3-D land seismic has been moderately successful within the last half decade (Harris et al., 1996; Brown et al., 2002). The Reservoir Characterization Group (RCG) at Colorado School of Mines has studied and reported on two of the best known projects (Vacuum Field, New Mexico, and Weyburn Field, Saskatchewan). Historically, 3-D surveys monitoring changes in reservoir properties after the injection of miscible

CO_2 have consisted of a baseline survey and a post- or late-production survey only (Terrell et al., 2002; Acuna and Davis, 2001; Chapman et al., 2000; Harris et al., 1996). Two time-slices do not permit assessment of the uncertainty in either the rate of change with time at fixed locations or the rate of spatial change between locations. At least four 3-D surveys, separated by time, are required to achieve the minimum degrees of freedom to assess temporal changes, and additional surveys will provide more detailed information.

Acquisition

This single patch design includes 810 shot points and 240 receiver stations covering about 3.6 km^2 (Figure 1). Based on reservoir simulations of the flood, the CO_2 front will form a 10-acre pie-shaped pattern with two producing wells at the corners and the CO_2 injector well in the center. Some movement is modeled to also occur out to the north of the recovery pattern area and is contained and controlled by injection in the northwest and monitored by a low-producing well in the northeast. The design provides uniform 20 to 24-fold coverage across an approximately 600 m $\times$ 450 m area centered on the flood pattern from start-up to breakthrough. Moving further away from the CO_2 injector, the two water injection wells planned for containment are all within the minimum 12-fold boundary. Two 2-D, 2-C shear wave lines intersect near the injection well and extend about 600 m away from the injector, and four 2-D, 2-C shear lines form a 400 m $\times$ 400 m box around the injector.

Patch design was optimized for bin size, X_{min}, X_{max}, fold, fold taper, migration aperture, squareness, and azimuthal distribution. Initial patch designs have limited bin size to a maximum 10 m $\times$ 10 m area while maintaining uniform fold. Shot lines are perpendicular to receiver lines and staggered to form a modified brick pattern. This pattern makes access and movement along shot lines precarious in some areas. This style patch does complicate the acquisition (source and receiver deployments), but it provides the optimum traces and trace distribution for each bin.

A 240-channel Geometrics Geode distributed system networked to a StrataVisor NZ acquisition controller recorded the seismic data. A single IVI minivibII with a one-of-a-kind prototype high-output Atlas rotary control valve swept 5 times at each source location with the first sweep used only to compact the ground. Vibrator movements were orchestrated using a digital map and real-time guidance using a Trimble DGPS. Sweep frequencies for the P-wave survey ranged from around 25 to 250 Hz, each with a 10 second duration. Receivers were three digital grade 10 Hz Mark Products Ultra2w geophones wired in series with 14 cm oversized spikes. For each survey, geophones were planted in a fresh spot but within a 0.5-m of the station location as defined during the initial survey. The three-geophone spread formed a 1 m equilateral triangle.

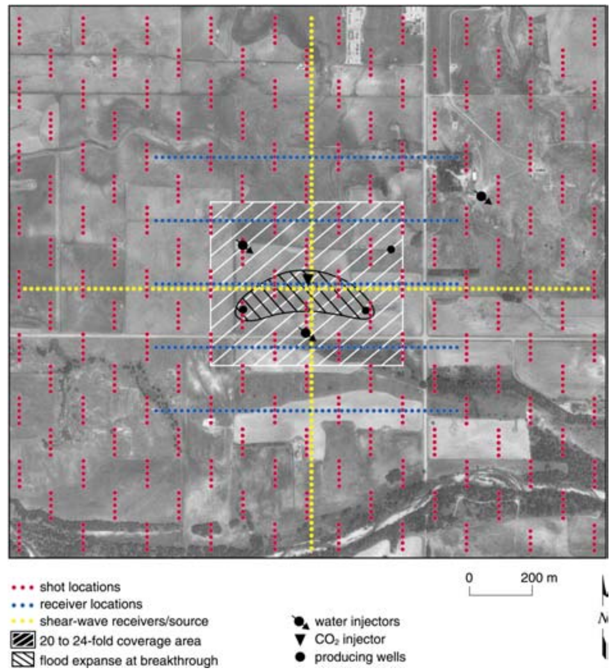

Figure 1. Orthophoto with preliminary 3-D survey design overlaying the wells involved with the CO_2 injection program. The flood extent at breakthrough (indicated by black crosshatching) is fully within the uniform 20 to 24-fold area of the survey. These 810 shot stations and 240 receiver stations will be occupied twelve times in 4½ years before, during, and after flood activities.

Data Observations

Data quality from the baseline survey was excellent (Figure 2). Data were cross-correlated with the synthetic pilot trace after whole trace gain was applied boosting the amplitude of the high frequency signal (1 second AGC scale). After correlation, coherent noise with an arrival pattern that changed from sweep-to-sweep (vehicles) was removed by zeroing affected portions of the data. Once the signal-to-noise ratio was maximized on each correlated sweep the last four (five sweeps were recorded at each site, but the first sweep was only used to seat the base plate) sweeps were then vertically stacked.

With simple spectral balancing (band limited spiking deconvolution) the dominant frequency of the reflection increased from around 70 Hz to over 100 Hz, which equates to an improvement in resolution potential from 10 m to around 8 m at depths in excess of 910 m (700 ms). As the data processing continued, the dominant frequency returning from 910 m has exceeded 140 Hz, thereby providing vertical resolution potential of around 4 m with an upper useable corner frequency of over 200 Hz making the thinnest possible bed resolution at

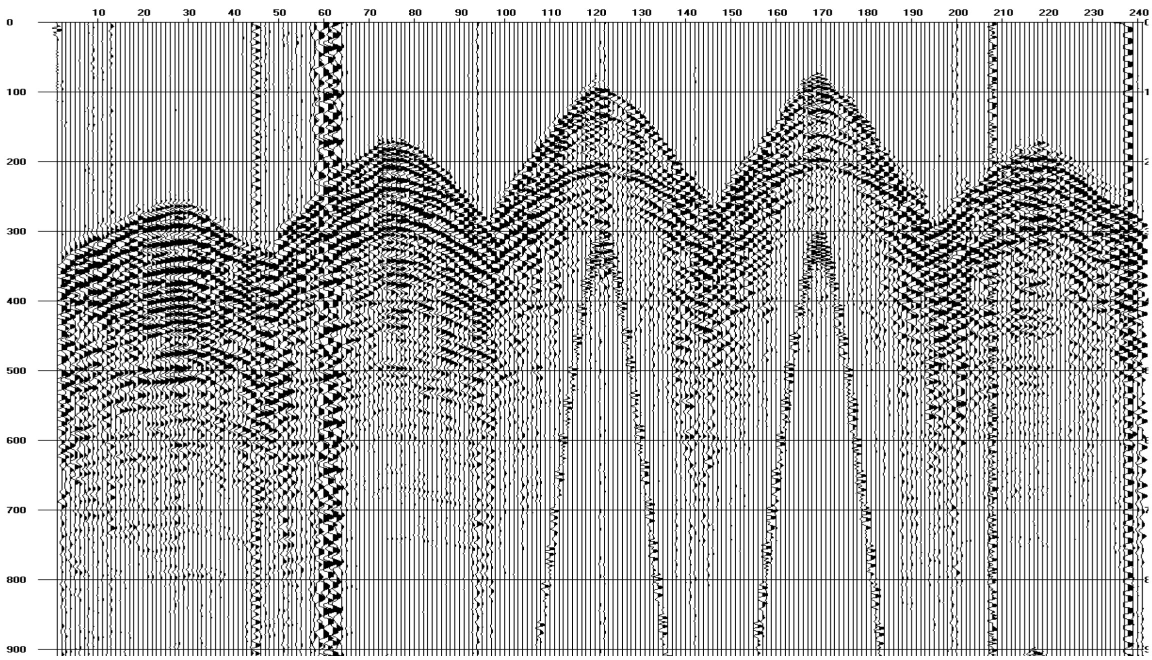

Figure 2. Correlated shot gather from station 19047, near center of the receiver spread.

around 3 m within the L-KC. Approximate two-way travel time to the L-KC using NMO calculated average velocities is around 700 ms. Several high quality reflections are evident between 500 and 800 ms. The top of the Arbuckle is likely the reflection at around 750-800 ms on longer offset traces with basement around 800 ms.

A subtle yet noticeable increase in the amplitude of reflections from within the CO_2 injection interval observed on shot gathers is consistent with seismic models and with expected movement of the CO_2 as predicted by reservoir simulators (Figure 3). Signal strength, frequency content, and source wavelet comparisons suggest little variation in data quality occurred resulting from the six-week stagger between the recording of these data sets.

Fluid Replacement

Fluid composition effects on P-wave velocity, and in turn on the seismic response from a hydrocarbon reservoir, is expected to vary from one rock type to another as well as from one porosity to another for the same rock type. In this fluid replacement (CO_2 replacing brine) case study, using Gassmann's relations, variations in P-wave velocity as a result of changes in pore fluid composition in average sands and carbonates have been modeled with the aim of highlighting the challenging situation of our approximately 20-30% porosity case study (Figure 4).

The variation in velocity for a given saturation, in response to porosity variations, is more pronounced in sands than in carbonates; as the porosity increases, variation in velocity in response to gas saturation becomes more pronounced regardless of rock type. In our case study, due to the thinness of the reservoir and a velocity around 2000 m/sec, reflections push-down effects as a result of CO_2-related velocity decrease

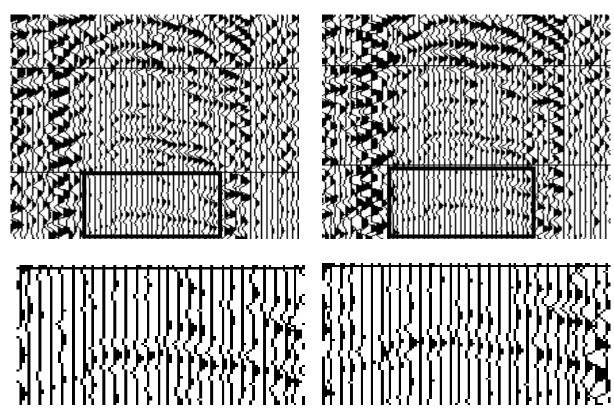

Figure 3. Before CO_2 (left) and after CO_2 (right). This enlarged section of the shot gather from station 19047 is from line 2. Reflections from the middle portion of the record have midpoints within a few hundred meters of the injection well and therefore are sampling the zone currently within the CO_2 flood.

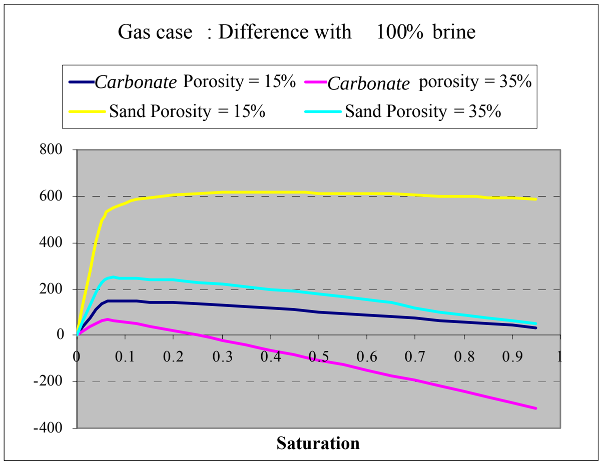

Figure 4. Relative change in P-wave velocity predicted by Gassmann's relations for gas replacements of brine in average sand and carbonates; the higher the porosity the more sensitive the velocity variation to gas saturation.

is unlikely to be detectable, nevertheless amplitude and frequency attributes are feasible tools of monitoring/quantifying injected CO_2. The decrease in seismic velocities at the target zone is expected to increase resolution of monitor surveys at the target zone.

Conclusions

Shot gathers possess a dominant frequency below that necessary to uniquely resolve the top and bottom of the C Zone (2 m thick) interval CO_2 is being injected into, but high enough to fully image the 4 m thick pay zone. Changes in amplitude characteristics are expected as the reflectivity of this entire interval changes with the arrival of CO_2. The higher the frequency of recorded reflections the greater the percentage change in the wavelet characteristics as a result of changes in fluid properties within the C Zone and therefore the greater the difference and distinguishability between pre- and post-CO_2 seismic data.

Without doubt high dynamic range and low noise threshold equipment and prototype components used to acquire these 3-D data more than doubled the overall signal-to-noise ratio and noticeably boosted the dominant frequency over conventional equipment. The 24-bit Geometrics Geode and a minivibII with a high output Atlas rotary valve dramatically (four times the power and 6 dB increase in dynamic range) elevated the potential effectiveness of this technique to monitor, track, and allow prediction of CO_2 movement while maintaining an extremely low cost per survey. Cost of this type survey is significantly less than a conventional operation.

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