4D seismic monitoring of the miscible CO_2 flood of Hall-Gurney Field, Kansas, U.S.

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Time-lapse seismic monitoring of enhanced oil recovery (EOR) programs has been described by several authors over the last 15 years. Advances in equalization techniques have allowed legacy data (in some cases 15 years prior to a monitoring survey) to be used as a baseline. Sensitivity of seismic data to subtle changes in pore composition has been notably improved with the development of dozens of new attribute analysis techniques in the last several years.

Unique to our application is the use of nonamplitude, noninversion attributes for monitoring the effectiveness of EOR in thin, shallow (less than 1000 m) carbonates. Considering the very thin (< 5 m) reservoir interval, this first-time, high-resolution 4D survey needed to be highly repeatable, low-cost, high signal-to-noise, and include several repeat surveys prior to breakthrough. Development of a highly accurate map of CO_2 progression through this field was complicated by difficulties propagating high-frequency signal in this near-surface setting, maintaining uniform fold coverage throughout the optimum offset range, vulnerability of signal to contamination by ground roll and air-coupled wave within the noise cone, weak fluid effects due to high carbonate stiffness, and complexity in porosity distribution.

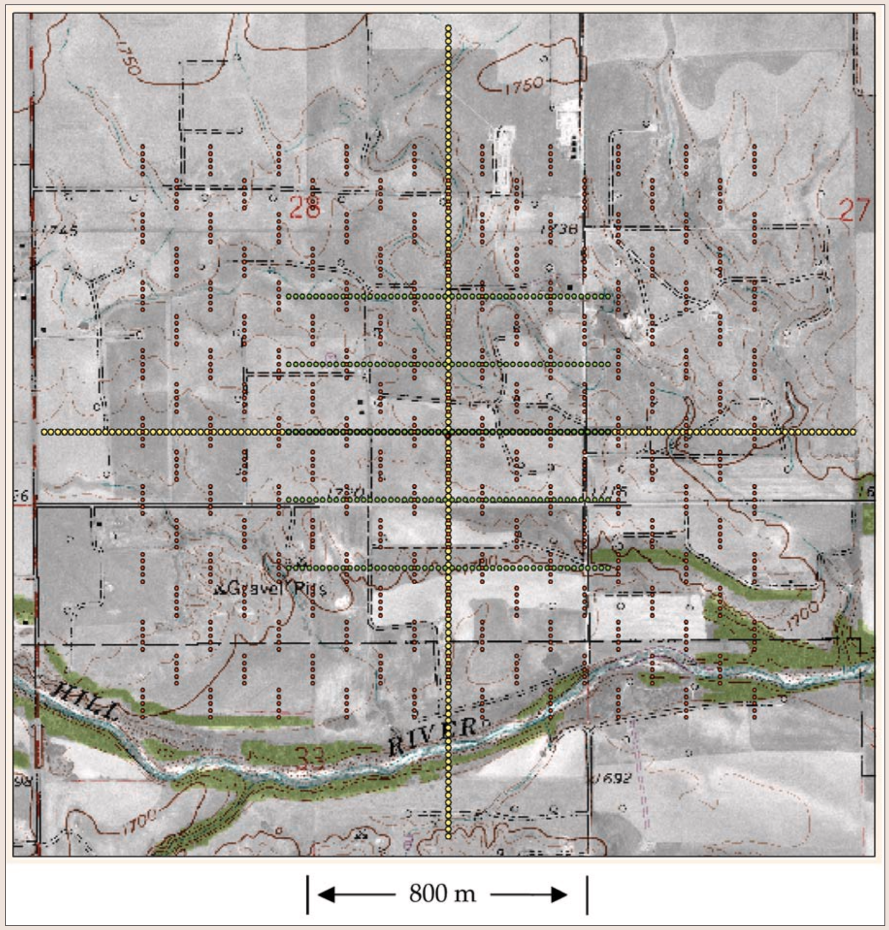

Figure 1. This orthophoto is from the Colliver lease southeast of Russell, Kansas. It is overlain by the current working 3D compressional- and shear-wave, high-resolution seismic-reflection survey to be acquired 12 times over the next six years. The center of this grid is approximately 6 m north of the injection well. Yellow dots indicate the shear-wave profile, green dots are the P-wave receivers, and red dots are the P-wave source points.

Primary and secondary production phases of the 70-year-old Hall-Gurney Field are nearly done. The Pennsylvanian Lansing-Kansas City (L-KC) groups have yielded 90 million bls of the 155 million bls cumulative production in the multipay field. Primary production was begun in 1931 and was followed by extensive waterflooding in the 1950s-60s. Waterfloods reached their economic limits in the 1970s-80s but bypassed oil represents a significant resource for CO_2 miscible flooding, a third development phase.

Reservoir rock of the Hall-Gurney oil field consists of shallow (about 900 m), thin (3.5-5 m), oomoldic limestone layers in L-KC with largely moldic porosities that decrease downward from around 35% to 12%. This reservoir is similar to many fields throughout the midcontinent area of the U.S. with respect to development stage, size of recoverable reserves, and the need for a well-monitored EOR program.

In this feasibility study, we have addressed several time-lapse EOR-CO_2 monitoring questions and problems primarily associated with thin (near or at temporal resolution) limestone reservoirs. These key objectives include:

- Designing a cost-effective, highly repeatable single pattern for this small-field CO_2 demonstration, characterized by its economic merits (small channel numbers, small single source, minimal crew resources), optimized acquisition parameters (uniform fold, large azimuthal and offset distribution, and relatively small bin size), and minimal need for postacquisition equalization.
- Establishing a processing flow that minimized data-specific operations, preserved reflection properties (amplitude, frequency, and phase), and eliminated as much noise as possible.
- Defining interpretation tools that most effectively discriminate changes in pore fluid both rapidly and with minimal processing requirements.

Interpretation objectives were met using a somewhat innovative approach to attribute analysis. The most noteworthy of these approaches were:

- Selection of a wide time window (24 ms) based 4D-AIF (average instantaneous frequency) attribute as a monitoring tool because its variability region for the target reservoir was modeled to be much higher than its back-

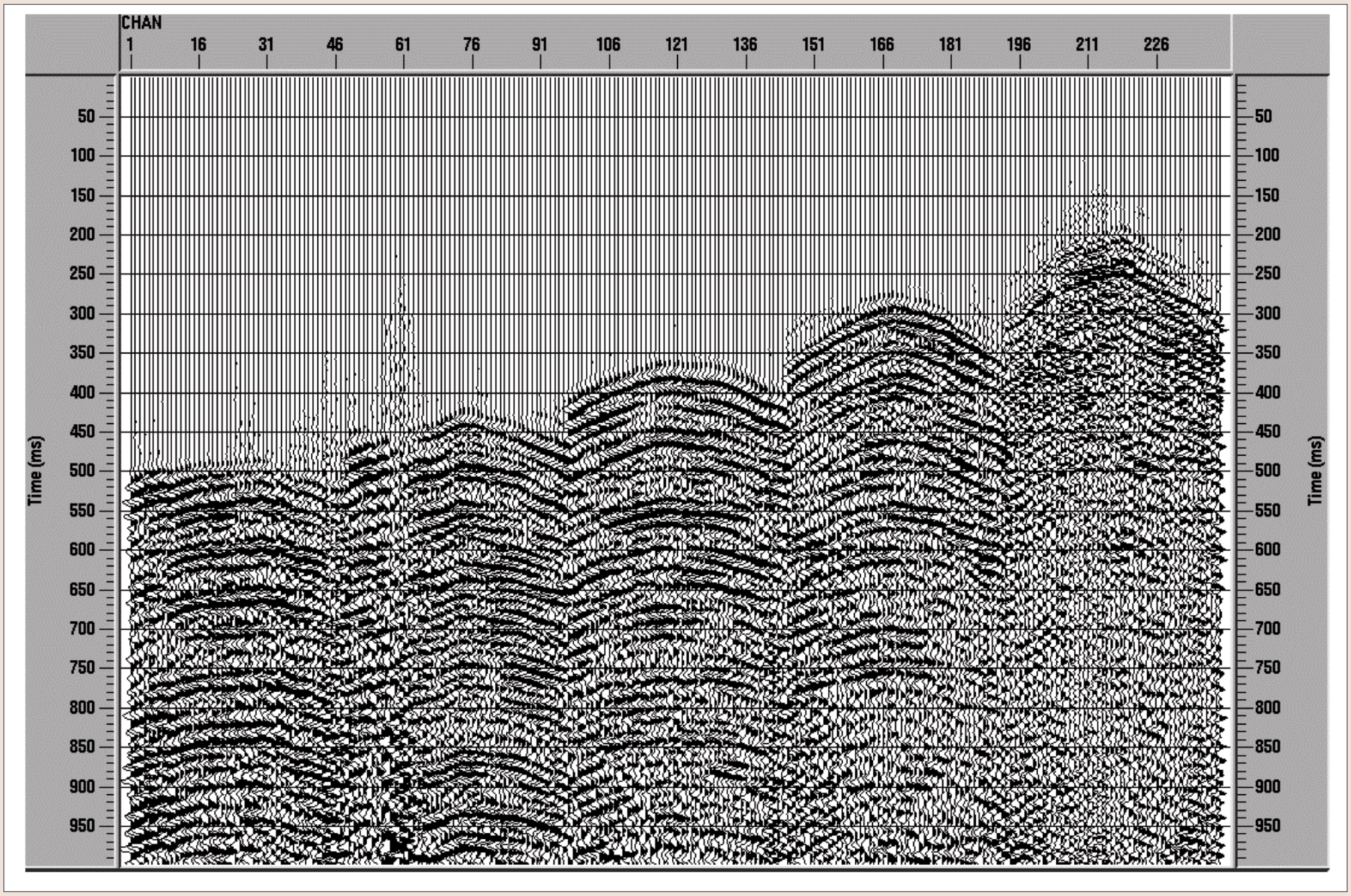

Figure 2. *Shot gather with source off south end of receiver grid. Reflections between 570 and 700 ms (depending on offset) are from the interval of interest.*

ground level. Amplitude variability near the limit of resolution, on the other hand, is in the decaying part of amplitude response.

- Development of a time-efficient and weak-anomaly preserving approach for balancing AIF maps instead of prior bulk seismic balancing, which potentially conceals or destroys expected CO_2-related anomalies.
- Tuning up all stages (data acquisition, processing, and interpretation) during the baseline phase to ensure optimization and maximize potential for successful 4D-seismic monitoring in this very difficult setting (shallow, thin carbonates).

We have successfully mapped the EOR-CO_2 spatial expansion utilizing AIF-seismic attribute maps for one base survey (November 2003) and three monitor surveys (January, March, and June 2004). The unprecedented survey-to-survey time-sampling frequency of acquired and planned surveys allows both tight control on the accuracy of CO_2 mapping and the nonlinear progression of the CO_2 front. This reduced sample rate prebreakthrough allows better integration with production data and assessment of sweep efficiency.

Geologic setting. The target of this EOR-CO_2 miscible flood is a thin, oomoldic limestone member (Plattsburg) "C zone" of the L-KC in central Kansas, deposited on a shallow marine shelf as part of a sequence of Upper Pennsylvanian depositional cyclothems.

Reservoir rocks were deposited as coarse-grained ooid sands in shallowing-upward fourth-order sequences and concentrated on bathymetric highs on a broad Kansas shelf. Subaerial exposure and meteoric water percolation caused ooid dissolution and resulted in oomoldic grainstones. Modern wireline logs and core data from the recently drilled CO_2 injection well validate general reservoir models based on data from midcentury development of this field, but also show previously unrecognized reservoir complexity. The CO_2 target zone (thickness of 3.6-6 m) is within up to three stacked, shallowing-upward cycles contained within a single higher-order shallowing-upward sequence accompanied by vertically increasing porosity and permeability. Regional development of these carbonate-dominated cyclothems was predominantly controlled by the eustatics sea level. Some have suggested glacial-eustatic cyclothems should be basic units for Pennsylvanian sequence-stratigraphic analysis.

Seismic data acquisition and processing. A modified brick style, single-patch survey was designed to make it economically feasible to carry out the time-lapse surveys at a relatively short (about two month) survey-to-survey time spacing and to require a data-gathering time span of about a week for each survey. The source area is about 3.6 km^2 with full-fold coverage on the order of 1×1 km (Figure 1). This coverage area is an order of magnitude larger than the anticipated flood area as predicted by reservoir models. Successive, closely time-spaced 3D seismic surveys to monitor the progress of the flood front sweeping through the reservoir provide a detailed spatially and temporally continuous characterization (a true 4D survey), permitting progressive dynamic adjustments to the reservoir models.

Acquisition of the 3D surveys (to date one base and three monitor surveys) for the 4D seismic monitoring pro-

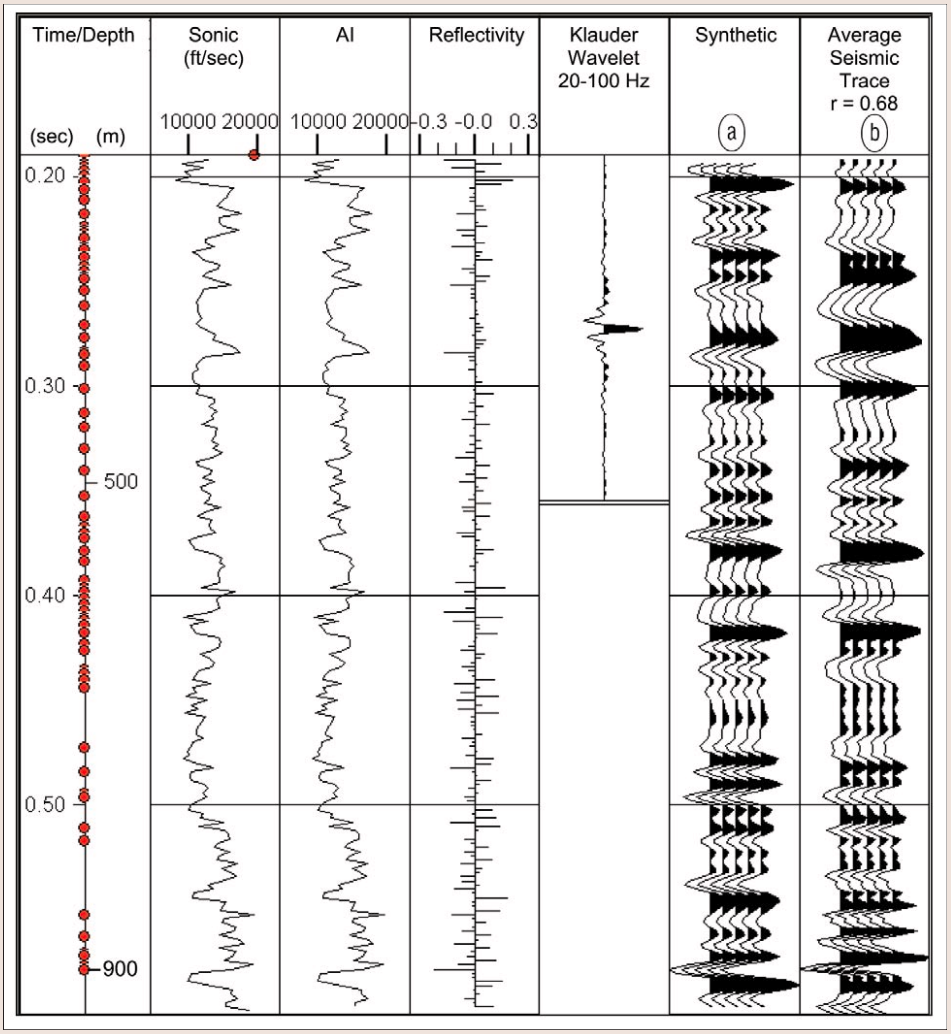

Figure 3. Synthetic (a) compared to average (b) real seismic trace near the CO_2-injection well.

ject began in November 2003 with a start up of CO_2 injection in December 2003. Digital data from preliminary DGPS surveys were used to guide site preparations and were integral to the construction of an extremely accurate and precise station-grid map (source and receivers). The station-grid map incorporated the 3D seismic-survey designs with the site-specific information and allowances for surface obstacles. Digital terrain maps with vibrator routes were built for all 800+ source locations across the site. Of the 810 shot stations possible with the design used, 798 were occupied for all surveys. Considering the six-year duration of this surface seismic-monitoring project, time spent at the early stages to accurately map each detail of data acquisition ensured maximum correlations between repeat surveys and minimized the need for radical equalization procedures during data processing.

An IVI minivib II running a prototype Atlas rotary servovalve generated 10-s linear upsweeps spanning the 20-250 Hz frequency range in a temporally uniform fashion. The first of the five sweeps was designed to seat the pad (compact the ground sufficiently that subsequent sweeps are as consistent as possible) while the remaining four sweeps were vertically stacked (once appropriate noise is edited from each) to enhance the signal-to-noise ratio. Ground-force plots with more than 8000 lbs of force at frequencies greater than 150 Hz were monitored closely to ensure optimum vibrator performance. Data quality was good with high-resolution reflections evident throughout the interval of interest at around 550 ms (Figure 2).

Each receiver line was located with a Trimble DGPS to ensure straight grid lines, with deviations in line-to-line spacing not exceeding 0.2 m. Three Mark Products U2 10-Hz geophones with 14-cm spikes were placed at the point of a half-meter equilateral triangle centered on the receiver station. Each receiver was planted at the base of a hole dug down through the sod and into firm soil. This ensures good coupling and reduces the effects of wind noise.

Nineteen shot lines and 240 receiver stations on a five-line layout constitute a single swath. To maximize squareness, an equal shot- and receiver-station spacing of 20 m was used with shot lines separated by 100 m and receiver lines separated by 200 m. Source progression through this spread consisted of five consecutive shot stations followed by the next five consecutive shot stations skipped. A bin size of 10 × 10 m and maximum fold of 24 resulted from our survey design. A grid rotation during CMP binning improved the uniformity of fold and source-receiver distributions.

The seismic data processing flow has been kept as simple as possible and the same for all data sets, thereby avoiding or at least minimizing processing-induced changes that may complicate mapping differential EOR-CO_2 seismic signatures. Major problems encountered pertained to source-generated linear noise and long-offset NMO undercorrections and frequency decay. Substantial offset-introduced difficulties in trying to preserve seismic-signal characteristics essential for the more demanding needs of high-resolution imaging were also identified and overcome. A majority of the data processing was completed using Promax on a SGI workstation. Key processing steps included:

- surface-consistent deconvolution
- Radon (τ-p) analysis and filtering for eradicating linear noise
- true-amplitude recovery with a spatially varying smooth-velocity field

The spectral characteristics of the stacked data provide a dominant frequency band from around 55 Hz to just over 100 Hz with a 16 db/octave average power fall-off rate up to a maximum usable frequency of just over 160 Hz, with the dominant frequency in the target zone over 90 Hz. The spectral characteristics of the data, the thinness of the target zone, and an NMO velocity around 3000 m/s favor using time-window-based attributes centered on the top of the L-KC seismic event. This approach was extremely effective in capturing the pore-fluid change in the seismic signature of the target interval, which is encoded in the L-KC seismic event.

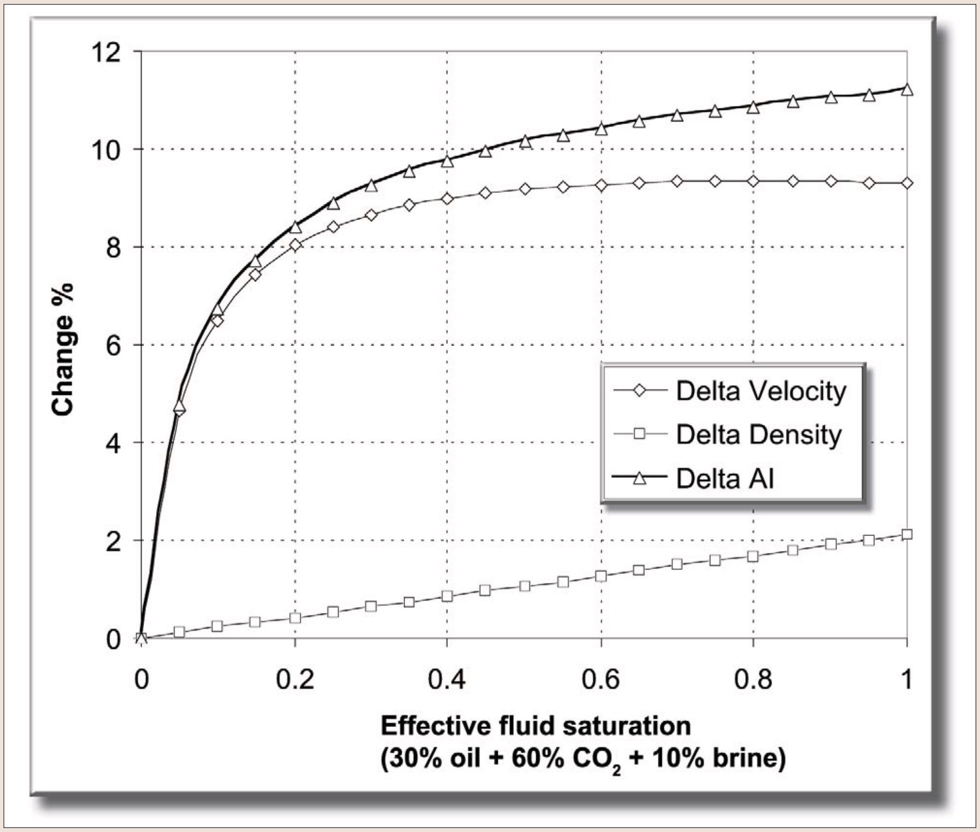

Figure 4. *Gassmann modeling. Percentage of property change equivalent to effective fluid (30% oil + 60% CO_2 + 10% brine) compared to 100% brine (pressure of 11 Mpa and temperature of 35°C).*

Synthetic-seismic traces produced from a sonic log of the CO_2 injection well correlate extremely well to real CMP-stacked traces from that area (Figure 3). The target interval has a very distinct seismic response.

Petrophysical properties and pore-fluid changes. Porosities in the oomoldic limestones of the target Plattsburg limestone range up to 35% and permeabilities range from 0.01 to 400 md. Permeability is principally controlled by porosity, oomold connectivity, and connection created by matrix crushing and fracturing. Permeability is also influenced by oomold diameter, oomold packing, and matrix properties. Calculated waterflood-susceptibility curves exhibit recovery efficiencies ranging from 56.2% to 66.3% of the oil in place (38.5-50.7% of pore space). These recoveries are for samples exhibiting porosities of 24-25.3% and permeability of 19.8-27.5 md. Residual oil saturation (averaging 30%) to waterflood is a critical variable for carbon dioxide miscible flooding because this represents the target resource. Unlike siliciclastic rocks, seismic velocities in carbonates are greatly dependent not only on porosity but also on pore-shape/porosity-type-high moldic carbonate porosities, resulting from diagenetic dissolution of grains, correlate with extraordinarily higher velocities than other similar carbonate porosities.

Nonuniform pore-fluid acoustic-property changes resulting from associated changes in reservoir pressures within the pilot study area—ranging from 11.7×10^6 N/m^2 (1700 psi) at the injection well to 2.7×10^6 N/m^2 (400 psi) near wells 12 and 13—and the associated continuum of CO_2 proportions in the pore-fluid composition significantly complicate calculations of the effective pore-fluid properties, generalized over the entire flood-pattern. Consequently, we have attempted to get an approximate bulk snapshot of the change in seismic properties resulting from the injection process. Previous studies have both empirically and theoretically found that both P- and S-wave velocities decrease in a carbonate rock when CO_2 is injected at pore pressures from 8.3×10^6 N/m^2 to 17.9×10^6 N/m^2 (1200-2600 psi).

Individual bulk moduli and densities of pore fluids can be calculated using approximate relationships. Gassmann's relations can be used to estimate rock-bulk modulus change for the two (effective fluid) pore-fluid compositions in proximity to the injection well. For our case the two-fluid composition includes the combination of oil-water and miscible—CO_2+oil-water—where the effective bulk modulus for a given pore-fluid composition is given by

$$\frac{1}{k_{effl}} = \sum_i \frac{S_i}{k_i}$$

where K_{effl} is the effective bulk modulus of the fluid mixture, k_i denotes the bulk moduli of the individual phases, and S_i their saturations.

By inserting the calculated effective fluid-bulk moduli of the two mixtures into Gassmann's relationship, the rock-bulk modulus change due to CO_2 injection ([CO_2+oil]+water) can be predicted. Effective pore-fluid density is calculated as fractional saturation weighted average of the constituting fluids. A velocity form of Gassmann's relation was used to calculate the velocity change due to CO_2 injection ([CO_2+oil]+water). Unlike many carbonates reservoirs, the relatively uniform petrophysical and lithological properties of the target oomoldic limestone interval make it amenable to Gassmann's type of fluid-replacement modeling. CO_2-induced acoustic-impedance changes of up to 11% are expected based on these calculations (Figure 4).

Seismic attribute analysis. Instantaneous complex-trace attributes provide a powerful quantitative description of the seismic waveform. This genome of the seismic wavelet allows us to capitalize on the sampling density of modern 3D-seismic data and is sufficiently robust to consistently highlight reservoir property changes targeted by time-lapse seismic monitoring of reservoir-fluid replacement.

Monitoring CO_2 floods in carbonate reservoirs with conventional 3D land seismic has been moderately successful within the last half-decade. In this study we have adopted a processing flow that refrains from operations that might harm or dilute weak anomalies (e.g., bulk-seismic volume cross-equalization). Highly repeatable seismic-data-acquisition surveys greatly diminish the need for cross-equalization of data collected as part of this 4D survey. Only minor color-scale adjustments were required to enhance the anomaly associated with CO_2 injection on attribute maps.

In the interpretation stage we took advantage of the sensitivity of instantaneous frequency (IF) to lithologic properties and therefore relative changes in those properties

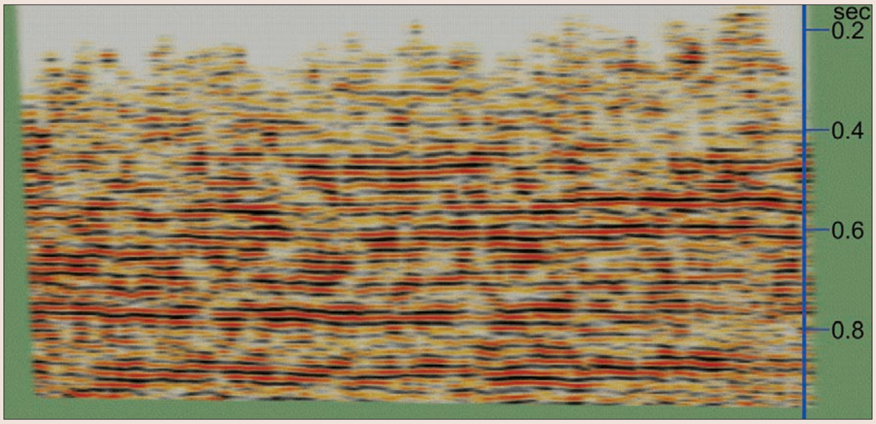

Figure 5. 2D slice of 3D volume with wiggle trace amplitudes represented in color. Coherency is quite good, but work is still under way to ensure true amplitudes have been preserved through all processing steps. A few amplitude anomalies resulting from noise-reduction processes are still evident on this section.

associated with CO_2 replacement. To counter the undesirable reputation IF has for oversensitivity to noise and its partiality to nongeologic variability, we applied both a spatial (5-trace) and temporal (24-ms) averaging routine, resulting in each map point being an average of 120 IF data points.

Results and discussion. Processed CMP cross sections through the seismic-data volume demonstrate the generally good quality these data possess (Figure 5). Reflection coherency through the time interval (550 ms) expected for reflections from the reservoir is sufficient for mapping the horizon throughout the volume. Some variability in coherency is related to noise suppression.

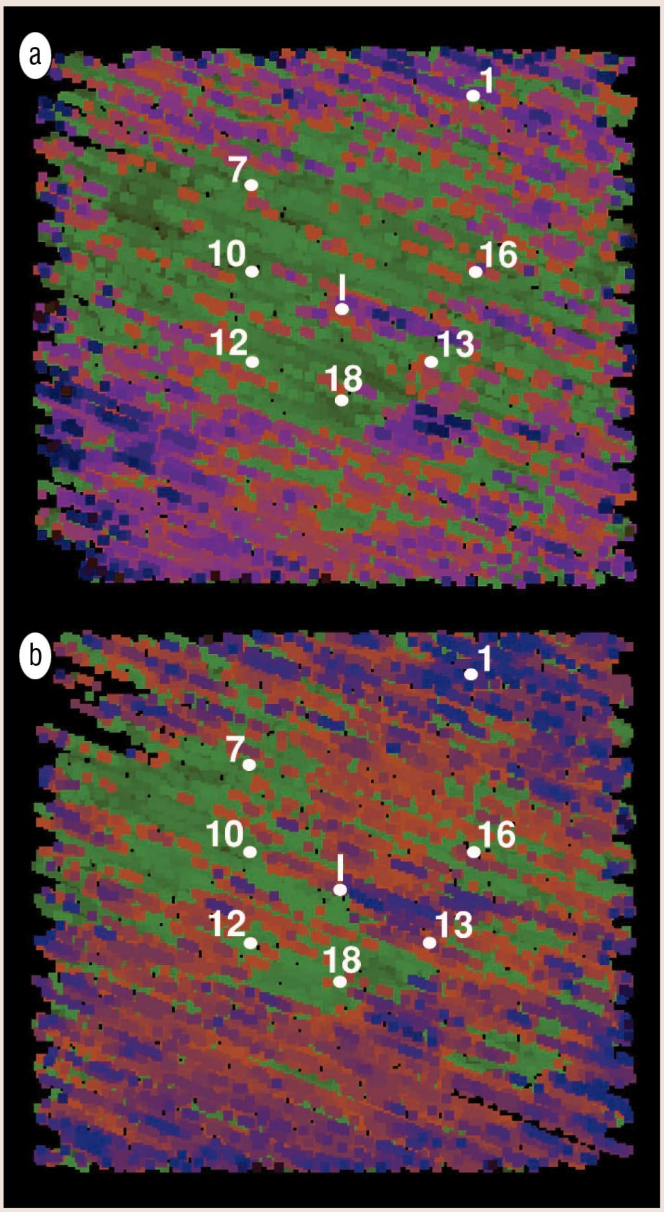

Figure 6. Instantaneous-frequency plots from baseline (a) and monitor survey (b). Well locations are identified. Change between surveys is evident. Once this 24-ms slice is rendered down to the horizon of interest, a more defined anomaly will be revealed.

Analysis and comparison of the baseline and monitoring surveys show changes in instantaneous frequency within the study area (Figure 6). Because of the thickness of the seismic volume and IF response issues, interpreting these data are limited to identification of areas where changes occur between surveys.

In general, changes on the monitor surveys relative to the baseline survey are predominantly north of CO_2-injection well I (CO_2 I1). Changes are evident south of CO_2 I1, but they appear less coherent as a mass. Volumetric analysis precludes the possibility that change observed in the entire region represents significant CO_2 invasion. Insufficient CO_2 volume was injected at the time of the first monitor survey to affect this entire area simultaneously. However, seismic response will noticeably change with a small-percentage change in saturation of CO_2. As well, considering the size of the Fresnel zone, "fingering" will appear enlarged on seismic data. Depending on the geometry of the "fingering," seismic images depicting an apparent large uniform "cloud" could easily represent several thin zones of higher CO_2 saturation moving through the reservoir.

When one examines the seismic-attribute responses to changes in thickness of thin layers (thickness less than seismic wavelet), it is evident that amplitude remains unchanged over about 15% of time-thickness changes, whereas IF is fully responsive (increasing or decreasing) over the entire range of time-thickness changes near or less than a seismic wavelength. Time-thickness variations of our target interval fall within this subreflection-wavelength range; therefore, changes in seismic wavelengths expected as CO_2 is injected into the reservoir zone could be invisible to amplitude analysis while clearly evident on IF plots.

Due to both spatial seismic-resolution limitations and the need to average the computed IF values for increased robustness of AIF-maps, the spatial area of the interpreted anomaly is expected to be larger than the actual CO_2-invaded area. It is, therefore, important to constrain delineating the boundaries of the interpreted CO_2 anomaly by volumetric modeling based on the injected CO_2 amounts.

Ideally, to best accomplish the objectives of any EOR program, the greatest benefit would come from not only mapping the flood advance but also predicting where the flood front might most likely move. Several attribute maps provide important and consistent insights into the geologic variability of this site. After review of the seismic-similarity map for the same target zone, geologic discontinuities can be identified that might affect or even control the advance of the CO_2 invasion. As well, lineaments observed in IF and instantaneous-amplitude plots suggest lithologic and structural variability is present and could represent control features. Lineaments interpreted on these attribute plots are quite consistent with geologic features interpreted on structure and porosity maps of the reservoir.

Conclusions. Increased use of seismic techniques to monitor enhanced-oil-recovery processes in fields with small net-pay thickness has been constrained by concerns for balancing EOR costs and expected return, as well as technical challenges arising from resolution and/or sensitivity of seismic response to limited changes in composition of pore fluids. In this case study we adopted a cost-effective, highly repeatable, 4D-optimized, single-pattern/patch seismic data-acquisition approach with several 3D data sets collected during the six months between the start of injection and breakthrough and several more surveys within the first two years to evaluate the feasibility of imaging changes associated with the "water alternated with gas" (WAG) stage. Furthermore, by incorporating noninversion-based seismic-attribute analysis, we were able to significantly reduce the time and cost of processing and interpretation of these data. In light of our seismic modeling, we targeted a 24-ms-thick time slice which included the approximately 1-ms-thick EOR-CO_2 injection interval-using an average instantaneous-frequency attribute (AIF). This analysis approach was quick and proved sensitive to changes in this very thin layer ($\approx$ 5 m or in the vicinity of $1/4\lambda$). Changes in amplitude response related to decreases in velocity from pore-fluid replacement within this time interval were much lower relative to background values than observed in AIF analysis. Carefully color-balanced AIF-attribute maps established the overall area affected by the injected EOR-CO_2. The approximate area identified as the "CO_2 anomaly" is in agreement with pressure-gradient measurements, time-lapse CO_2 volumetrics, and seismically interpreted geologic discontinuities.

Suggested reading. "Integration of rock physics, reservoir simulation, and timelapse seismic data for reservoir characterization at Weyburn Field, Saskatchewan" by Brown et al. (SEG 2002 *Expanded Abstracts*). "Seismic properties of pore fluids" by Barzle and Wang (*Geophysics*, 1992). "Factors controlling elastic properties in carbonate sediments and rocks" by Eberli et al. (*TLE*, 2003). "Seismic monitoring of a CO_2 flood in a carbonate reservoir: A rock physics study" by Wang et al (*Geophysics*, 1998). "Experimental verification of seismic monitoring of CO_2 injection in carbonate reservoirs" by Harris et al. (SEG 1996 *Expanded Abstracts*). TLE

Acknowledgments: Support for this work was provided by the U.S. Department of Energy (NETL); we greatly appreciate the support provided by Paul West and Bill Lawson. Thanks to Murfin Drilling Company for access to their on-site resources, especially Kevin Axelson. Marla Adkins-Heljeson's editorial review greatly improved this paper. Mary Brohammer's work preparing this manuscript and annotating the figures was invaluable.

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