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Rock Physics and Seismic Modeling Guided Application of 4D-Seismic Attributes to Monitoring Enhanced Oil Recovery CO_2-Flood in a Thin Carbonate Reservoir, Hall Gurney Field, Kansas, U.S.A.

Summary

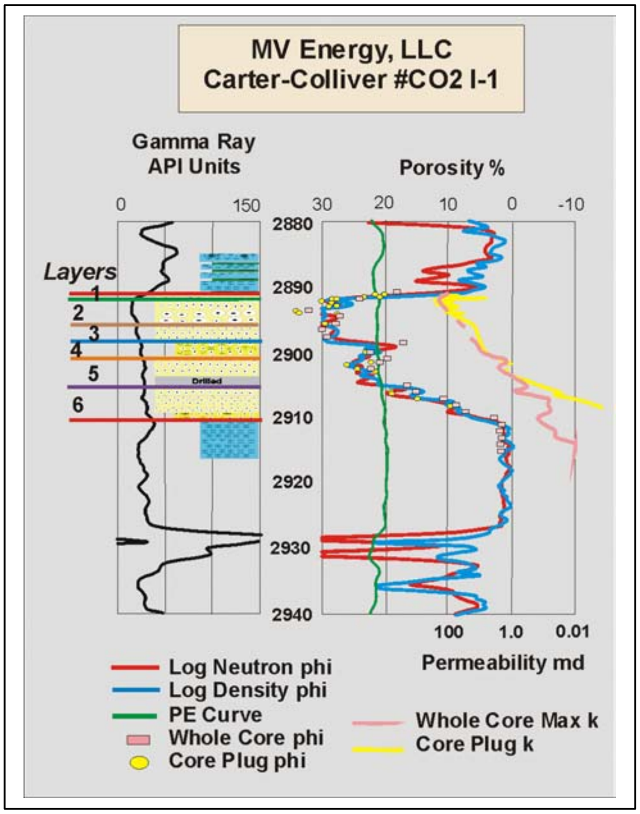
The efficiency of enhanced oil recovery (EOR) programs in carbonate reservoirs rely heavily on having an accurate reservoir characterization. It is advantageous that we have accumulated reservoir knowledge inferred from production history and/or legacy 3D seismic data. 4D/time lapse seismic monitoring of a pilot carbon dioxide flood in a thin, shallow-shelf, oomoldic carbonate reservoir in Hall Gurney field, Kansas, has aided CO_2-flood management and highlights the necessity of updating reservoir simulation models. Use of an unconventional approach to data acquisition, and interpretation of high-resolution time-lapse/4D seismic data effectively imaged movement of miscible CO_2 through a thin (about 5 m), shallow (about 900 m), oomoldic limestone reservoir during the on-going pilot EOR program. Extremely short survey-to-survey temporal separations (two months) of four high-resolution time-lapse surveys enabled the evaluation of high-resolution time-lapse seismic sensitivity to changes in pore-fluid composition. We adopted a non-conventional, weak anomaly-sensitive, interpretation approach of time-lapse seismic data. Simulations uniquely displaying reservoir heterogeneities using rock physics and seismic attributes clearly depict a well-constrained fluid flow scenario that is consistent with production data.

Rock physics and seismic modeling aided the understanding of the response of selected seismic amplitude attributes to both effective pore-fluid and geometrical time-thickness variations in this thin carbonate target. The combined effect of pore-fluid and geometrical time-thickness variations reflects a highly non-linear amplitude response. Selected 4D-seismic attribute maps that have undergone weak-anomaly enhancement through color balancing successfully monitored the movement of the injected miscible EOR-CO_2 front and illuminated heterogeneities affecting/controlling flood bank expansion.

Introduction

Use of time-lapse seismic to monitor enhanced oil recovery (EOR) programs in carbonates has seen limited success. This has been due to various non-seismic factors such as the highly heterogeneous nature of carbonates, diagenetic complications of porosity distribution, shallow depth and thinness of many carbonate reservoirs, and low compressibilities that reduce fluid-effect. Other complications related to seismic imaging include resolution limitations, low signal-to-noise ratios, low-fold coverage at shallow depths, near-surface irregularities, and small-field economic constraints.

Time lapse (4D) seismic monitoring/aiding in reservoir management programs provides valuable information (Lumley, 2004; Koster et al., 2000; Fanchi, 2001; Robertson 1989) which, when delivered in a timely cost-effective manner, is critical to supporting dynamic reservoir



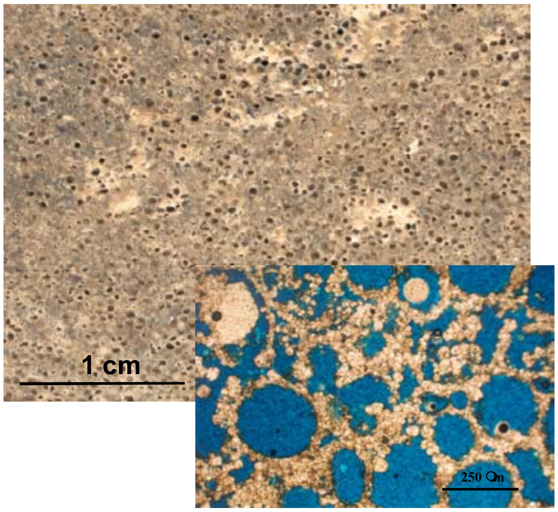


Fig. 1: *L-KC "C" zone exhibits decreasing porosity and permeability with increasing depth (left); Core photo and plane light thin section (2903 ft, 884.8 m) showing blue-dye impregnated oomoldic porosity and recrystallized limestone matrix framework. Crushing of matrix is evident (right) (after Dubois et al, 2001).*

management in terms of EOR-assessment and monitoring, more constraints on reservoir simulation, compartmentalization, and in terms of placement of infill-wells. Thus cost-effectiveness, shortness of turnaround time, and sensitivity to subtle production and/or EOR reservoir changes are very critical assets of robust and economic TL-seismic application. Success of TL seismic applicability has been proven mainly for offshore case studies of thick clastic reservoirs (Waal and Calvert, 2003) offshore Gulf of Mexico and North Sea (Boyd-Gorst et al., 2001) with lower risk according to technical risk assessment scoring (Lumley et al., 1997)

TL seismic changes "anomalies" incurred by enhanced oil recovery from or Carbon Dioxide sequestration in low compressibility "stiff" carbonate reservoirs, are likely to be so weak to the extent of being blended into the background noise on seismic attributes difference maps. Those expectedly weak TL anomalies "high risk cases" lie in what is classified as "stretch portfolio"(Waal and.Calvert, 2003) of time-lapse application to reservoir management practices.

In this pilot study, we integrated Gassmann fluid replacement (Gassmann, 1951) and thin layer seismic modeling (Widess 1973; Kallweit and Wood, 1982) for establishing the seismic signature of a combined pore fluid composition and apparent time thickness changes on 4D-seismic amplitude attribute.

Geological Setting

The target of this EOR-CO_2 miscible flood is a thin, oomoldic carbonate formation (Plattsburg) "C zone" of the Lansing-Kansas City group in central Kansas, deposited on a shallow marine shelf as part of a sequence of Upper Pennsylvanian depositional cyclothems. Reservoir rocks were deposited as fine-medium grained ooid sands in shallowing-upward fourth-order sequences, concentrated on bathymetric highs on a broad Kansas shelf. Subaerial exposure and meteoric water percolation caused porous cementation of interparticle porosity and ooid dissolution and resulted in oomoldic grainstones (Dubois et al. 2001; Byrnes et al. 2000). Modern wireline logs and core data from the recently-drilled CO_2 injection well validate general reservoir models based on data from mid-century development of this field, but also show previously unrecognized reservoir complexity. The CO_2 target zone "C" (Fig. 1) (thickness of 3.6-6 m) comprises up to three stacked, shallowing-upward cycles contained within a single higher-order shallowing-upward sequence accompanied by vertically upward increasing porosity and permeability. 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 the tertiary EOR-CO_2 miscible flooding.

Seismic modeling and rock physics

In this thin layer pilot case study, it is essential to take into consideration that variations in seismic velocity introduced by variations in pore fluid composition result in a complex time lapse seismic response that results not only from rock-properties but also from apparent "due to velocity change" thickness change. Seismic modeling of a thinning layer (Fig. 2) indicates that seismic amplitude may increase or decrease depending on whether thickness increases render layer thicknesses less than or greater than 1/2 dominant seismic wavelength. We therefore took notice that the CO2-related amplitude dimming might be weakened or enforced by thickness related effects, depending on the region of thickness variability.

Nonuniform pore-fluid acoustic-property changes resulting from associated changes in reservoir pressures and facies within the pilot study area—ranging from 11.7 _ 106 N/m2 (1700 psi) at the injection well to 2.7 _ 106 N/m2 (400 psi) near wells 12 and 13—and the associated continuum of CO2 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 effects of pore-fluid composition changes.

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 CO2-oil-water.

Unlike many carbonates reservoirs where significant facies changes can occur over very short distance, the relative uniformity laterally of petrophysical and lithological properties in the target oomoldic limestone interval should allow the use of Gassmann's type of fluid-replacement modeling. CO2-induced acoustic-impedance changes of up to 11% are expected based on these calculations.

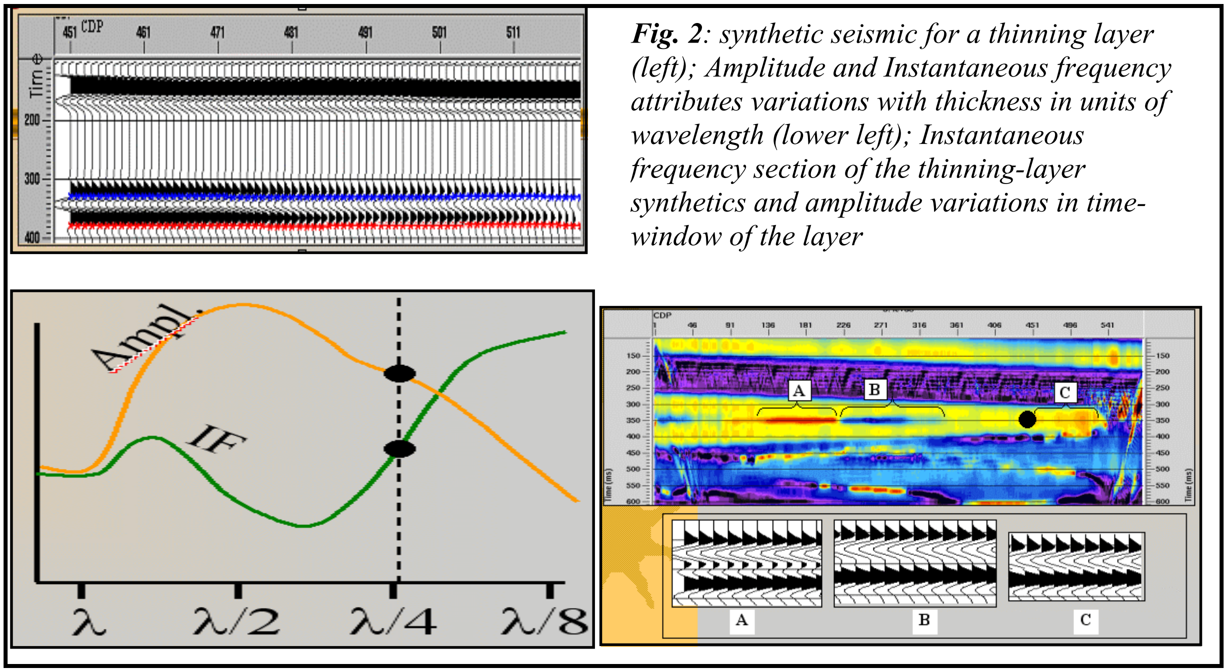


Fig. 2: *synthetic seismic for a thinning layer (left); Amplitude and Instantaneous frequency attributes variations with thickness in units of wavelength (lower left); Instantaneous frequency section of the thinning-layer synthetics and amplitude variations in time-window of the layer*

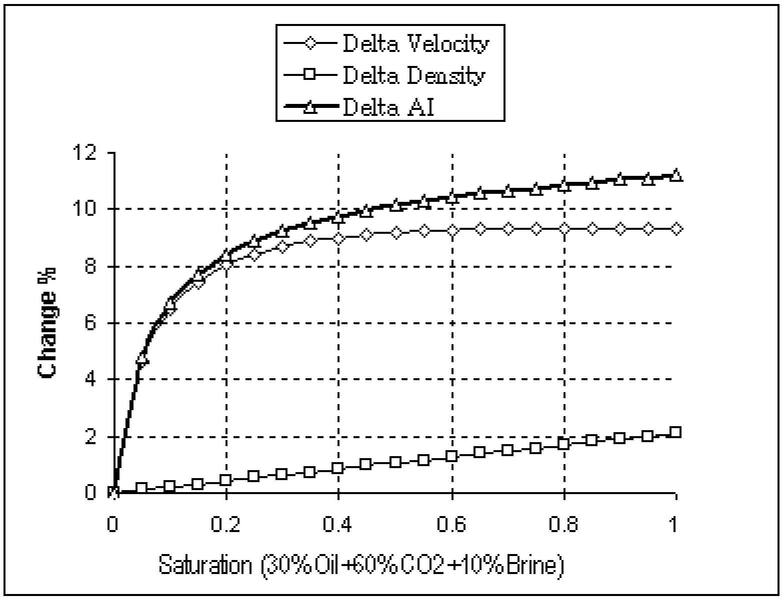
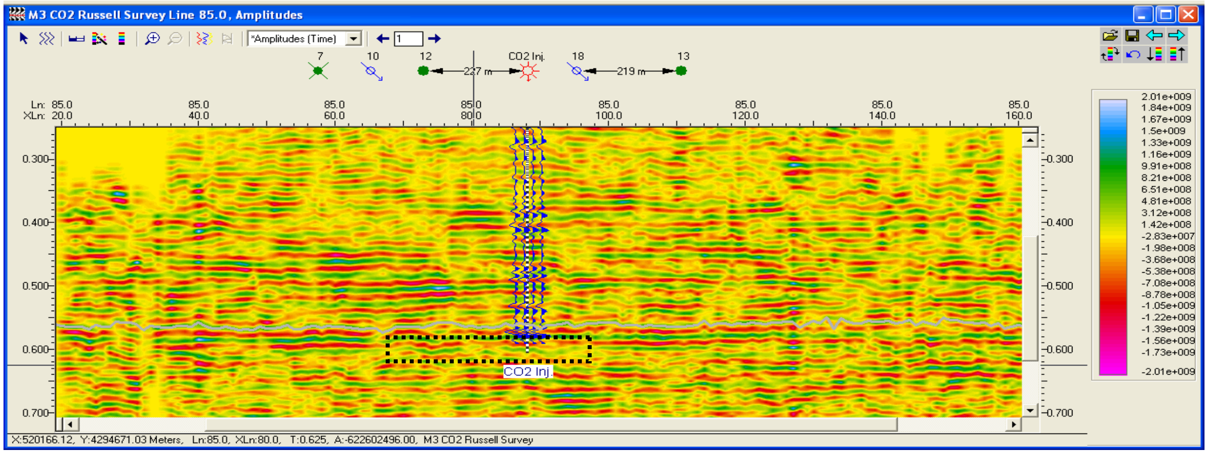


Fig. 3: *Gassman modeling. Percentage of property change equivalent to effective fluid (30% Oil + 60% CO2 + 10% Brine) compared to 100 % (30% Oil + 70% Brine) (pressure of 11 Mpa and temp. of 35^{o}C).*

4D-Seismic monitoring of tertiary EOR-CO$_2$ flood

Having to image a weak (in the vicinity of background noise) EOR-CO$_2$ change, we developed and applied an approach, which avoid differencing TL-data or attribute with the corresponding baseline data or attribute. Our approach uses parallel progressive blanking (PPB), color balancing and color focusing of both baseline and TL amplitude envelope attribute and analysis of resulting textural differences. In the PPB method of interpretation, no differencing is applied; PPB is applied to both the baseline and the TL-amplitude envelope maps and a comparison/search for TL-textural reservoir signature is carried out. We applied the PPB method to balanced and normalized amplitude envelope maps of one baseline and three monitor amplitude envelope maps We selected the amplitude envelope or reflection strength seismic attribute because it is insensitive to small phase shifts differences, for which correction may not have been applied, between the baseline and

TL-datasets. A typical seismic section and synthetic traces are shown in Figure 4. The target seismic horizon (grey) is at about 570 ms time depth tracking a peak amplitude value. The amplitude envelope attribute was extracted because of the desirable property of insensitivity to small phase shifts, providing easier comparison across surveys. The progressive advance (Fig. 5 a, b, c, d) of the injected CO_2 expansion has been successfully monitored by PPB application and is consistent with field well production data.



M3 CO2 Russell Survey Line 85.0, Amplitudes

*Amplitudes (Time)

X:520166.12, Y:4294671.03 Meters, Ln:85.0, XLn:80.0, T:0.625, A:-622602496.00, M3 CO2 Russell Survey

Fig. 4*: Seismic amplitude section, interpreted target top horizon (grey), and seismic synthetics at well* CO_2*I-1. Gas shadow effects are evident below time horizon in the vicinity of the injection well.*

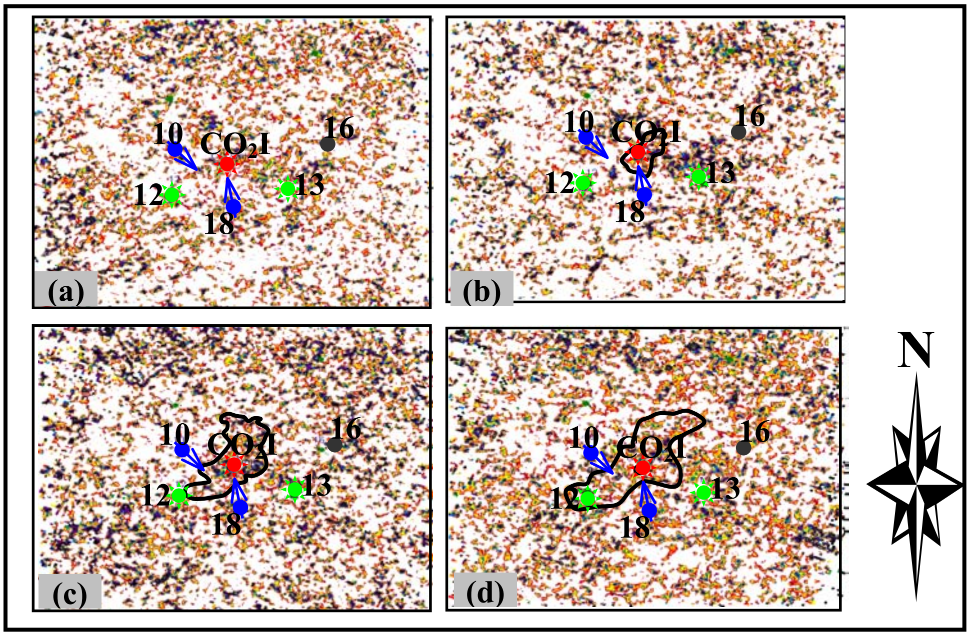


Fig. 5*: PPB and color focusing of balanced and normalized amplitude envelope attributes for* CO_2 *flood bank (outlined) monitoring; (a) baseline, November 2003; (b) Monitor I, January 2004; (c) Monitor II, April 2004; (d) Monitor III, June 2004; Wells 10 and 18 water-injection, wells 12 and 13 oil producers, and well 16 observation.*

TL-seismic interpretation is consistent with and helped to understand field response data including: 1) TL indication of solvent "CO_2" breakthrough in well No. 12; and 2) delayed response and the interpretation of a permeability barrier between Well No. 13 and Well CO_2I#1; and 3) Reservoir simulation based prediction of CO_2 movement northwards from CO_2 injection well.

Conclusions

Time lapse seismic monitoring of EOR-CO_2 in below temporal resolution shallow thin carbonates is feasible. Spatial textural rather than sustainable magnitude TL-anomalies are to be expected in such cases. We therefore recommend using non-inversion direct seismic attributes, for monitoring EOR-CO2 flood developments. Close synergy with EOR-engineering field management team and timely updates of reservoir simulation is fundamental for maximizing benefits of TL-monitoring results.

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