GEOPHYSICAL CORNER

S-Waves Detect Reservoir Flows

The Geophysical Corner is a regular column in the EXPLORER, edited by R. Randy Ray. This month's column is titled "Multi-Component, Time-Lapse Seismology for Monitoring Reservoir Production Processes."

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Improving reservoir performance and enhancing hydrocarbon recovery are critical to the future of the petroleum industry – and to do this, it must be possible to characterize reservoir parameters, including fluid properties, their movement and pressure changes with time.

Multi-component, time-lapse seismology has great potential for monitoring fluid movements in reservoirs. The main reason is simply the presence of fluid-filled fractures.

Shear waves (S-waves) are much more sensitive than compressional waves (P-waves) to the presence of fractures or microfractures and the fluid content within the fracture network. Seismic shear wave anisotropy in the reservoir causes two shear modes to form (S_1 and S_2) and to propagate with different velocities.

The faster mode (S_1) propagates with its particle motion parallel to the open fracture direction, perpendicular to the minimum horizontal stress (S_3) in the reservoir – a phenomenon called S-wave splitting, or birefringence (Figure 1).

Seismic shear wave anisotropy is key to monitoring fluid property changes in fractured media.

First 4-D, 9-C Seismic Survey

The first time-lapse (4-D), multi-component (9-C) seismic surveys were acquired at Vacuum Field in Lea County, N.M.

At the Vacuum Field, shear wave (S-wave) and compressional wave (P-wave) seismic data were used to monitor reservoir fluid property changes associated with a carbon dioxide (CO_2) tertiary flood in the Permian San Andres Carbonate. Reservoir fluid properties – including viscosity, density, saturation and pressure changes – occur in response to CO_2 injection. Changes are caused by CO_2 and oil becoming a miscible phase with the oil in place.

These fluid property changes alter the interval velocity and attenuation of S-waves passing through the reservoir interval by up to 10 percent, but cause little (1 to 2 percent) or no measurable change in P-wave velocity and attenuation on the surface seismic data.

The Reservoir Characterization Project of the Colorado School of Mines (RCP) has conducted two studies at Vacuum Field:

❒ Phase I efforts centered on monitoring the injection of CO_2 from a single wellbore (Benson and Davis, 2000).

❒ Phase II is the dynamic reservoir characterization of a six-well CO_2 injection program, which includes the Phase-I wellbore (producing during Phase-II) (Wehner, et al, 2000).

The Vacuum Field was discovered in 1929 with the drilling of the Socony Vacuum State 1 well in Section 13-T17S-R34E of Lea County.

The Vacuum Field produces predominately from the San Andres Formation in a shallow-shelf carbonate depositional setting (Figure 2), which structurally is positioned on the shelf edge of the Permian Basin's Northwest Shelf. The structurally high shelf crest is located just west of the RCP study area.

Porosity and permeability within the productive zones average 11.8 percent and 22.0 md, respectively.

The San Andres gross pay zone can reach 600 feet in thickness, and is divided into two main pay zones: Upper and Lower San Andres.

The Lovington Sandstone, a silty interval, segregates the two zones.

Reservoir Characterization

At Central Vacuum Unit (CVU), S-wave splitting is the key to monitoring production processes associated with carbon dioxide (CO_2) flooding.

Fluid property changes produce variations in the velocities of the split S-waves passing through the reservoir interval. Reservoir fluids change in response to CO_2 and oil becoming a miscible phase in the presence of in-situ fluids.

Injected CO_2 also can create areas of anomalous reservoir pressure.

Both fluid and pressure changes are detected by S-wave splitting and velocities, because they are extremely sensitive to the local stress field caused by the natural fracturing in all rocks, especially carbonates.

Distinguishing Injected CO_2 From Injected Water

S-wave splitting can distinguish between effective stress changes associated with abnormal fluid pressures and fluid property change.

During Phase I of this study, a prominent S-wave splitting anomaly was detected to the south of a cyclic CO_2 injection well (CVU 97). This anomaly corresponds to the CO_2 flood bank that developed south of this temporary injection well (Figure 3, Phase I).

Noticeable around the periphery to this CO_2 anomaly are anisotropy anomalies of opposite sign related to offset wells that were used to contain the CO_2 bank through water injection. The sign change of S-wave anisotropy occurs because the relative velocities of the split S-waves reverse.

In the case of the miscible CO_2-oil bank, the S_2 velocity increased and S_1 decreased, whereas, in the case of water injection, the effective stress causes S_2 to decrease and S_1 to increase.

Similar effects were observed during the second phase of the monitoring study (Figure 3, Phase II). These results imply that S-wave anisotropy can be used to monitor secondary (water flooding) as well as tertiary (CO_2) methods in a spatial context beyond the wellbore.

The greatest need of tertiary recovery operations is to monitor and control the areal and vertical distribution of injected CO_2 in the reservoir. Controlled injection can maximize contact with the oil and optimize sweep efficiency so that oil is

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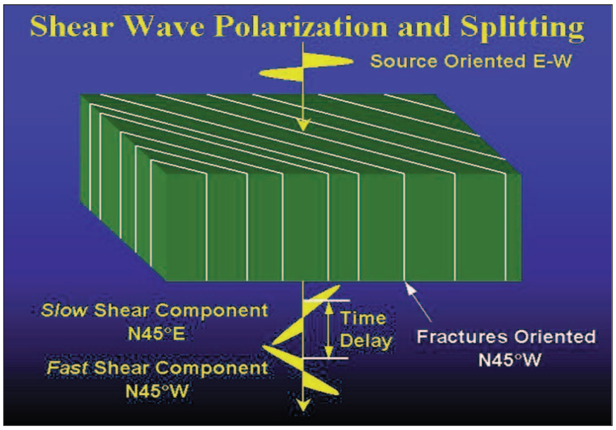

Figure 1. Shear-wave polarization and splitting in a fractured material. As an S-wave with an arbitrary polarization direction enters an anisotropic material, the wave splits into S_1 and S_2 components with different polarizations and different velocities. The wave polarized parallel to the fractures travels faster and is less attenuated that the wave polarized perpendicular to the fractures. After the S-waves emerge from the anisotropic material, they continue to propagate as two S-waves with different polarization directions.

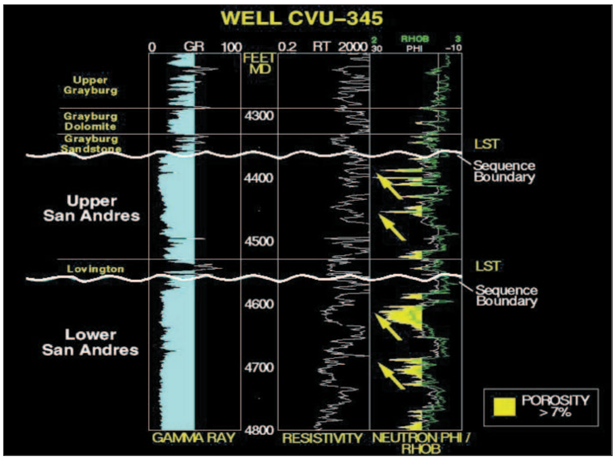

Figure 2. Type log for the Vacuum field area. The San Andres Formation is at an approximate depth of 4,300 feet and is the primary producing formation in the Vacuum Field.

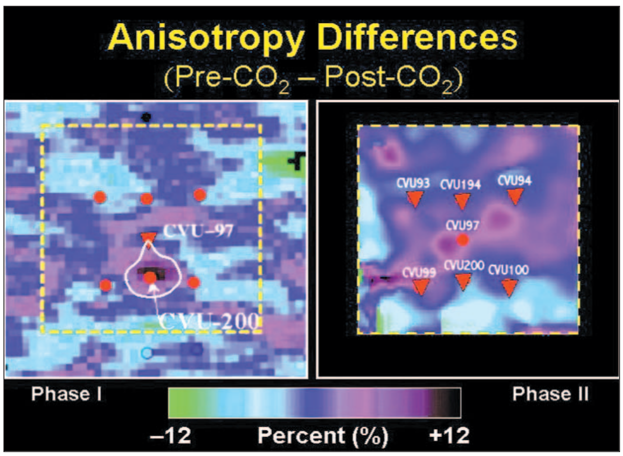

Figure 3. Time-lapse shear-wave velocity anisotropy differences. Phase I) CO_2 injection occurred at the CVU-97 well with a prominent S-wave anisotropy anomaly detected to the south. Phase II) CO_2 injection occurred at the six offset injectors (indicated by triangles). In the case of the miscible CO_2-oil bank, the S2 velocity increased and S_1 velocity decreased (purple), whereas, in the case of water injection, the change in effective stress causes the S_2 velocity to decrease and S_1 velocity to increase (blue).

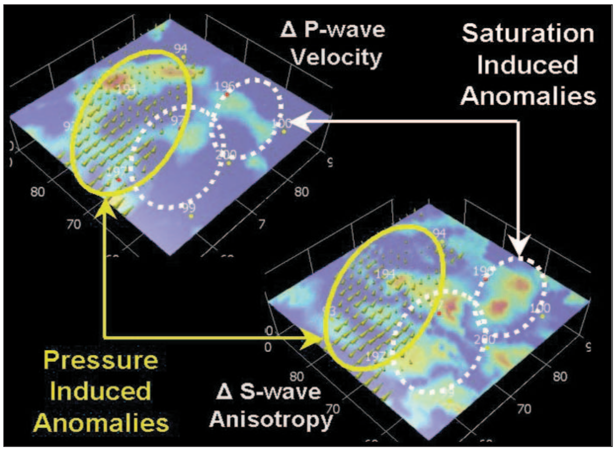

Figure 4. Phase II seismic anomalies. The upper diagram shows the time-lapse P-wave velocity differences while the lower diagram shows the time-lapse S-wave velocity anisotropy differences. Overlain on each diagram are the S-wave polarization direction differences (areas that have changes in the S-wave polarization direction). Areas of the reservoir that have P-wave velocity and S-wave polarization direction anomalies correspond to zones of the reservoir with pressure changes. Areas of the reservoir that have S-wave anisotropy anomalies correspond to zones with fluid saturation changes.

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not bypassed.

A spatial image of the tertiary flood-front was visualized by observing time-lapse anisotropy differences. This enables the lateral sweep efficiency of the reservoir to be monitored.

The vertical sweep efficiency can be detected through amplitude differentials of split S-waves. S_2 amplitude difference anomalies between the pre- and post-surveys occur dominantly in the Lower San Andres. This is highly encouraging, because S-wave anisotropy may provide higher vertical resolution, enabling a visualization of changes approaching the individual flow-unit scale.

The time-lapse seismic interpretation of the Phase II seismic data showed a differential seismic anisotropy anomaly between the baseline and monitoring survey that coincides with the tertiary flood bank (Figure 3, Phase II). This anomaly was measured over the entire reservoir interval, and is shown as a velocity anomaly where S_1 velocity decreased and S_2 velocity increased.

Figure 4 shows the correspondence between time-lapse P-wave velocity, time-lapse S-wave polarization direction and time-lapse S-wave velocity anisotropy anomalies. Using this information, it is possible to separate the effective stress changes associated with changing fluid pressure from the fluid saturation changes associated with the tertiary flood bank.

As a result, the tertiary flood bank – and its growth over time – can be monitored by this technology.

Conclusions

The study indicated that shear wave analysis provided higher resolution (than P-wave data) static reservoir characterization, allowing for visualization of inter-well distribution of secondary porosity, permeability and fracture zones.

Due to rigidity changes associated with fluid replacement in the reservoir, dynamic monitoring with shear wave data provided a means to actively follow the displacement of reservoir fluids with CO_2.

This dynamic reservoir characterization will provide the industry with the ability to be more proactive, rather than reactive, in the management of reservoirs.

(Editor's note: Benson and Davis are both with the Reservoir Characterization Project, Colorado School of Mines, Golden, Colo.)