Time-Lapse Borehole Case Study in Vacuum Field, New Mexico

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Summary

Two multicomponent vertical seismic profiles (VSPs) were recorded in an open well, 500 ft away from two carbon dioxide (CO_2) injectors in the Central Vacuum Unit, Lea County, New Mexico. The surveys were recorded one year apart with the baseline VSP, conducted prior to CO_2 injection and a monitoring survey, recorded after eight months of injection.

The processing and interpretation of the borehole seismic survey was necessary to interpret compartmentalization of the reservoir. Surface seismic data delineates faults with vertical displacement of 4-6 m but faults with less displacement require a higher resolution image to detect. Surface seismic 3D surveys showed fault and fracture zones connecting wells CVU-97 and CVU-200 (DeVault, 1997) (Figure 1). The borehole seismic data confirms these faults and fracture zones.

In addition, the time-lapse surveys show changes in seismic signals within the reservoir for both P- and S-waves. This observation demonstrates the value in using seismic borehole data for reservoir monitoring.

Introduction

High resolution time-lapse borehole studies are used to analyze the reservoir. The Reservoir Characterization Project (RCP) recorded time-lapse surface seismic and borehole seismic surveys, including VSP and 3D VSP. From the near offset VSP's, changes in attenuation and velocity were observed (Michaud, 2000). The goal is to extend the interpretation to the 3D case. This paper summarizes the fault interpretation and the time-lapse analysis of the 3D data.

Fault interpretation

The reservoir imagery was obtained from a 3D pre-stack depth migration performed by the Compagnie Générale de Géophysique (CGG) using a single velocity function derived from the first time arrivals at the VSP well. This dataset is interpreted with the objective to better understand the geological structure of the reservoir in the vicinity of the acquisition well. Indeed, the high frequency borehole data present an increased resolution of the reservoir architecture.

The fault interpretation begins from the interpretation of time sections of the 3D cube. As shown along the east-west line 34 on Figure 2, the faults are interpreted

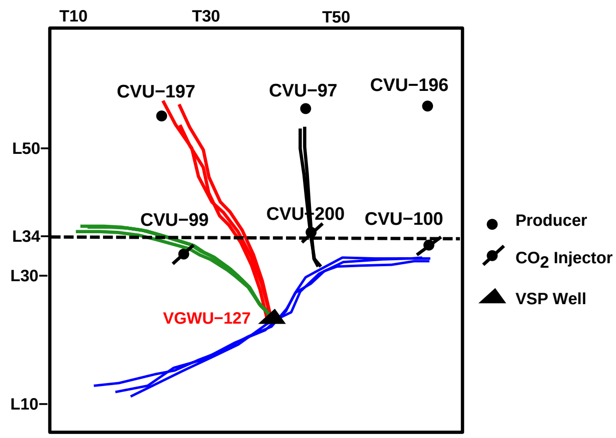

Fig. 1: Interpreted model for the fault structure of Vacuum Field over the San Andres reservoir. The east-west line 34 is represented by the dashed line.

from the San Andres reservoir up to the Yates Formation. To gain more confidence in the interpretation of these subtle seismic changes, a coherence analysis of the 3-D cube is performed to track the seismic discontinuities. Because of the subtle changes in the signal character and the coarse sampling of the migrated data, this coherency analysis is marginally successful. However, this analysis reveals a fault traversing east-west with a branch trending northeast at the vicinity of the VSP well and a fault connecting CVU-99 and VGWU-127. Two other north-south discontinuities are interpreted, north from the VSP well and CVU-200. The acquisition pattern leaves a footprint on the migrated image of the reservoir, inducing large areal discontinuities. These discontinuities can be reduced with a denser data grid. Nevertheless, these coherency zones corroborate the interpretation pursued on time sections, and allow us to image the faults and propose a fracture distribution.

These faults are compared with the structural interpretation of the San Andres performed on the surface seismic datasets. The east-west fault through the VSP well corresponds with the fault interpreted from the well logs and from the surface seismic. This fault was incorporated into the geological model to support the reservoir simulation. The other faults or fracture zones correspond with the fractures interpreted from coherency analysis on the surface seismic (Duranti, 2000). Indeed, the two faults oriented north from the VSP well are interpreted as a single fault from the surface seismic. Since the borehole dataset is laterally limited, the continuity of these two faults cannot be interpreted further north, but these two faults are more defined by the borehole data. These fractures were not interpreted as critical from the surface seismic analysis and were not incorporated into the geological model for reservoir simulation. However, even of small magnitude, fracture zones are meaningful in acting as fluid barriers or as fluid flow conduits within the reservoir.

From the geological interpretation, these discontinuities are associated with the main east-west fault running along the shelf edge. The bending of the east-west fault near the VSP well is associated with other fractures in the north direction. These discontinuities may connect the east-west fault running through the VSP well with another east-west fault going north of the survey.

To determine if these interpreted discontinuities are critical with regard to fluid flow in the reservoir, the well production data are considered. The biggest producer of the survey, CVU-97, and the two west and east producers, CVU-197 and CVU-196, indicate a north-south permeability trend. In addition, the producers south of the VSP well have a lower production rate. Consequently, the east-west fault running near the VSP well is interpreted as sealing. In addition, the CO_2 was mainly injected from the well CVU-200, which took twice as much as the two injectors, CVU-99 and CVU-100. The well CVU-200 is confirmed to be within a compartment with locally high permeability.

From this interpretation, the VSP well resides in a highly fractured area. This interpretation is in agreement with the interpretation of AVO and shear wave studies realized in RCP Phase VI and VII. Indeed, from AVO study, DeVault (1997) presented high shear wave velocity contrast within the San Andres reservoir around the area of CVU-200, CVU-97 and VSP well.

To summarize, the fault and fracture zones are interpreted to be associated with the main east-west fault, along the shelf edge of the carbonate platform. These fracture zones are interpreted based on amplitude dimming, horizon discontinuity and cross-coherency cube. These fractures are vertical with negligible displacement and are located at the reservoir level at 4500 ft. They are interpreted to compartmentalize the reservoir around each injector with the best fluid flow within the compartment of CVU-200. The injected fluid from CVU-200 is interpreted to flow north toward the producer CVU-97. Concerning the fluid injection invasion at the VSP well, since the medium is highly fractured, injected CO_2 may propagate along open fractures from either CVU-99 or CVU-200. VGWU-127 is at an equal distance from these two wells, but the injected fluid from either one of these two wells may not reach at the same time the VSP well, depending on the compartment of the reservoir where the VSP well is. The fluid from CVU-200 should propagate faster than the fluid from CVU-99. However, the maximum horizontal stress is oriented along the direction N120°E. Consequently, the resulting open fracture direction aligns with the well CVU-99, creating a possible path for the CO_2 to flow.

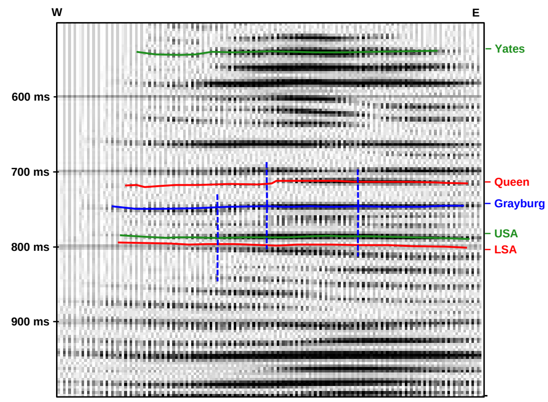

Fig. 2: P-wave time section over the east-west line 34, illustrating the interpretation of the main horizons and faults. Please refer to the Figure 1 for the line location.

Time-Lapse Analysis

The fracture interpretation indicates connection between the VSP well and the CO_2 injectors, 500 ft north. In addition, the near-offset analysis identifies significant changes of attenuation within the reservoir. The goal is to extend the time-lapse analysis to the 3D dataset.

The objective of comparing seismic surveys over time is to determine the changes occurring within the reservoir and to help in making decisions for enhancing the exploration and production of the reservoir. However, comparing different surveys is a difficult task and requires a normalization of the data via cross-equalization (Ross, 1996). Indeed, the data are not perfectly repeatable due to near-surface conditions, tool equipment or acquisition design differences. It is necessary to design a filter to apply to one of the two surveys in order to minimize the differences in time, amplitude and phase above the reservoir where no dynamic changes are expected. For the present data, the repeat survey was not recorded with the same tool. The tool of the baseline survey was CGG's SST500, composed of 12 levels, spaced every 10 m (32.81 ft) with a total length of 110 m (360.9 ft). The repeat survey was recorded with OYO's Advance Borehole Receiver (ABR), composed of 10 levels, spaced every 15 m (49.21 ft) with a total length of 135 m (442.9 ft).

The complete processing and interpretation is performed at the CSM along 2D lines of the 3D datasets. The downgoing waves are used as a reference for correcting differences in time from the near-surface conditions, and in amplitude and frequency from the difference of tool. However, after migration the time sections still need an additional equalization to minimize the obvious differences in the wavelet character and arrival times of the reflections over the entire record length. The migration used for the processing of the 2D lines is a 2D pre-stack migration for borehole seismic data. The same velocity is used for both surveys.

The equalization of the two surveys begins first with the filtering of the two datasets to the same bandpass frequencies: 15-20-70-80 Hz, for *P*-waves and 15-20-50-60 Hz, for *S*-waves. Then, the reflection time differences are corrected for one shallow reflector, Yates formation, with time picking and shifting to a single time value. The amplitude and phase are corrected with a cross-equalization filter designed over one single time window above the reservoir where the rock properties are assumed to remain unchanged over time. This time window is 200 ms for *P*-waves, and 400 ms for *S*-waves. The resulting cross-equalized traces present a clear repeatability for *P*-, S_1- and S_2-waves (Figure 3). Each figure represents the baseline and repeat traces cross-equalized for common shot points on the left side, and the maximum values of the difference traces on the right side.

After cross-equalization, the compressional waves have amplitude differences not only within but also above the reservoir. The changes in the amplitude within the reservoir occurs at the top of the Lower San Andres (LSA), where on the near-offset VSP, the Q factor was observed to increase. The amplitudes are observed to be lower on the repeat survey compared with the baseline survey at the top of LSA. On the fast shear waves, the only significant changes in the seismic wavelet between pre- and post-CO_2 injection occur at the top of the Lower San Andres. These changes occur due to a "slower" fast shear waves on the repeat survey compared with the baseline survey. The time difference of the reflections at the top of LSA is about 10 ms $\pm$ 2 ms, indicating a decrease of velocity of 10% $\pm$ 2% for an interval velocity computed over 100 ms. The slow shear waves change above the reservoir, similarly to the compressional waves. However, changes in the repeat survey within the reservoir are also observed at the top of the Lower San Andres with a decrease of the amplitude and velocity. The decrease of velocity is 5% $\pm$ 2%. Such changes on *P*- and *S*-waves reveal a change in the rigidity of the medium. Indeed, rigidity is expected to decrease with CO_2 flooding into the formation, inducing a decrease of the water-oil viscosity.

Slight changes are also observed within the Grayburg, east and west of the VSP well at around 500 ft, on both *P*- and *S*-waves. They have not reached the VSP well and are particularly strong on the S_1-waves. During the CO_2 injection, an issue concerns possible leakage in the Grayburg formation. Indeed, vertical fractures may connect the Lower San Andres with the Grayburg, which is a sandstone formation presenting two channelized deposits with a north-south trend trough the survey. One channel goes through CVU-99 and CVU-197, and the other one includes the VSP well, CVU-200 and CVU-97 (Pranter, 1999). A leakage from the Lower San Andres to the Grayburg is possibly observed on the cross-equalized data.

Additional changes in amplitude above the reservoir are related to noise and uncertainty in the data. The *P*- and S_2-waves may be more affected to the noise than the S_1-waves. The *P*-wave frequency range is wide and the cross-equalization may not succeed in fully equalize the signal over the frequency range. The repeat survey is noticed noisier than the baseline survey due to the difference in tool sensitivities. The S_2-waves are more attenuated than the S_1-waves and present more noise contamination: the Yates formation is not clearly represented on the S_2-wave time sections even after cross-equalization (Figure 3).

Changes in the seismic wavelet within the reservoir are observed between the two surveys. However, only fast shear waves present changes limited at the reservoir level. Both compressional and slow shear wave present changes above the reservoir, inducing a difficult interpretation on the significance of the changes within the reservoir. Are these data comparable even after this cross-equalization? Is an additional cross-equalization necessary and justified? Indeed, these two datasets are not recorded with the same tools, inducing possible difference in the signal between pre- and post-injection, even in the static zone, above the reservoir where the rock property is not expected to change. Another cross-equalization should then be necessary. After application of another cross-equalization over the same window, the differences are diminished, but still remain at the same locations.

To summarize, the cross-equalization presents value in comparing data recorded at different times and with different tools. The difference in amplitude, phase and velocity above the reservoir is reduced between the two surveys. The seismic signals at the top of the Lower San Andres are better revealed after cross-equalization in both *P*-and *S*-waves. Assuming the changes within the reservoir are due to changes in the rock property, they reveal the presence of CO_2 at this VSP well, 500 ft from two injectors, creating a decrease of velocity in both shear wave components.

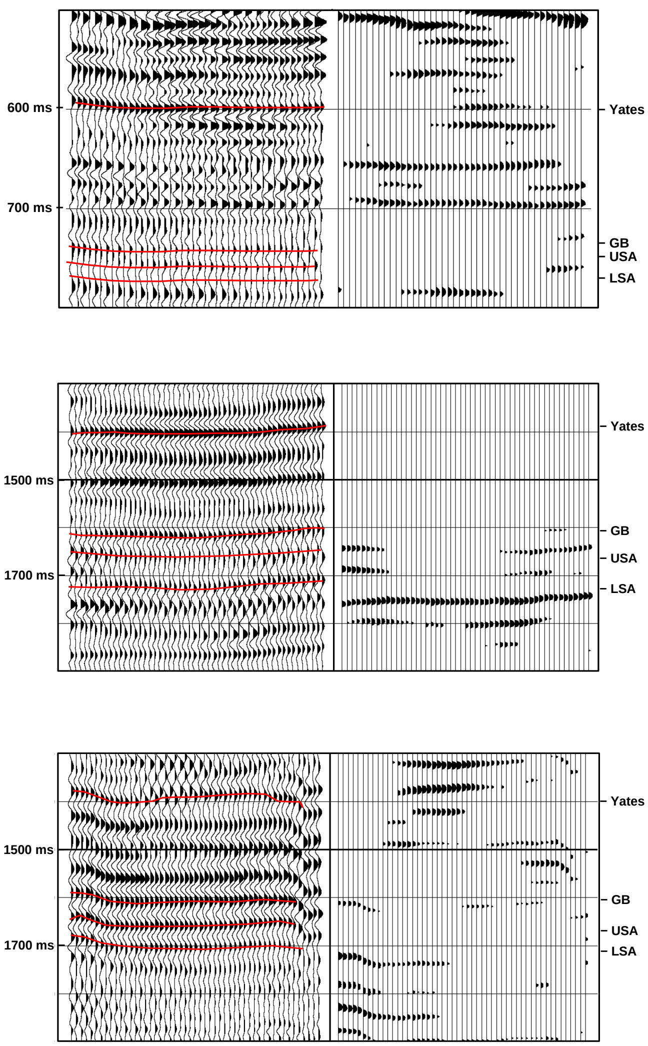

Fig. 3: Cross-equalized baseline and repeat on the east-west line 34 for P- (Top), S_1-(Center), and S_2-waves (Bottom). Each figure represents the baseline and repeat traces cross-equalized for common shot points on the left side, and the maximum values of the difference traces on the right side.

Conclusion

The interpretation of the borehole seismic data confirms the existence of fractures within the reservoir. These fracture zones play a critical role in the fluid flow within the reservoir. The reservoir is compartmentalized by faults and fractures with a north-south permeability trend.

The time-lapse analysis indicates CO_2 breakthrough to the VSP well from CVU-200 and CVU-99. P- and S-wave seismic data exhibit changes within the reservoir, at the top of the Lower San Andres. The cross-equalized data also show changes within the Grayburg formation, due to a leakage of CO_2.

The time-lapse analysis of the reflections at the San Andres reservoir shows promise in fluid monitoring associated with change in fluid viscosity in a carbonate reservoir. However, it is also important to maintain a high signal to noise ratio. Given the resolution of the borehole data, velocity changes are measured within the reservoir on shear wave data. Amplitude differences coincide with the zone of interest, identified from the near-offset study.

Acknowledgements

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