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Dynamic Reservoir Characterization at Central Vacuum Unit

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Abstract

Multicomponent, time-lapse seismology has great potential for monitoring production processes 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. Fractures introduce seismic anisotropy into a reservoir, causing two shear modes (S_1 and S_2) to propagate with different velocities and therefore different arrival times. This phenomenon is referred to as s-wave splitting or birefringence, and is critical for estimating fracture density (see Martin and Davis, 1987).

At Central Vacuum Unit (CVU), s-wave splitting is developing as an important key to monitoring production processes associated with carbon dioxide (CO_2) flooding. Fluid property changes associated with CO_2 flooding produce changes in the velocities of the split s-waves passing through the reservoir interval. Fluid properties change in response to CO_2 and oil becoming a miscible phase in the presence of in-situ fluids. S-wave splitting can also be used to identify areas of anomalous reservoir pressure. S-wave splitting and velocities are extremely sensitive to the local stress field because all rocks, especially carbonates, contain incipient networks of microfractures at a state of near-criticality (Zatsepin and Crampin, 1997).

S-wave splitting can assist in separating effective stress changes associated with abnormal fluid pressures from fluid property change. This conclusion is inferred by results of the CVU study. During the first phase, 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). It is believed that this anomaly corresponded to the tertiary flood bank that developed south of this temporary injection well (**Figure 1a**). Noticeable in the periphery to this 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, Phase-II of the monitoring study (**Figure 1b**). 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. This dynamic reservoir characterization could provide the industry with the ability to be more proactive than reactive in the management of reservoirs.

Introduction

This investigation was conducted under the auspices of the Reservoir Characterization Project (RCP), an industry sponsored consortium whose mission is to develop and apply 4-D (time-lapse), multicomponent seismology and associated technologies to economically improve reservoir performance and hydrocarbon recovery. The RCP conducted two studies at CVU. Efforts associated with Phase-I 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; inclusive of the Phase-I wellbore (producing during Phase-II).

By recording time-lapse, multicomponent (4-D, 3-C) seismic data, a reservoir can be probed dynamically, equating propagation characteristics to reservoir parameters, which change over time as the reservoir is exploited. Dynamic reservoir characterization is the name coined for this process. For dynamic reservoir characterization to succeed, several elements are required. First, static reservoir characterization begins with the acquisition of a baseline 3-D, 3-C seismic survey and formation of a reservoir model. To the extent that porosity and permeability, generally obtained or inferred from well data, can be integrated with multicomponent 3-D seismic data, distribution of these properties in the interwell space is key as a successful first step in the dynamic reservoir characterization process.

Secondly, the ability to integrate multiple seismic data sets into the reservoir model and to iterate with reservoir simulation is fundamental to the dynamic reservoir characterization process. Reservoir simulation is used to test and refine the reservoir model based on history matching actual results and observations. The final product of time lapse monitoring is a more accurate, dynamic reservoir model, which can be used to guide production drilling, (re)completion, and enhance reservoir management decisions. For any dynamic reservoir characterization project to succeed, the seismic monitoring survey(s) must produce accurate images of the dynamic changes in the reservoir and be tied to the reservoir simulation. Dynamic reservoir characterization begins when time-lapse difference anomalies are introduced into the simulation model in an effort to match the observed reservoir responses to previous expectations.

General Geological Setting

The CVU gained its name from its relative position within the Vacuum Field (**Figure 2**), which was discovered in 1929. CVU produces predominately from the San Andres Formation, in a shallow-shelf carbonate depositional setting. Structurally, CVU is positioned on the shelf edge of the Permian Basin's Northwest Shelf. The San Andres Formation dips off into the Delaware Basin and San Simon Channel to the south. The structurally high shelf crest is located just west of the RCP study area. Textures in the pay intervals are primarily packstones and grainstones of fusulinid/pelmatozoan and ooilitic/peloidal composition (Stoudt and Raines, 2000). Porosity and permeability within the productive zones average 11.8% and 22.0 md, respectively. At CVU, the San Andres gross pay zone can reach 600 feet (200 m) in thickness. It is divided into two main pay zones: Upper and Lower San Andres. The Lovington Sandstone, a silty tidal flat interval with little known effective flow-capacity, locally segregates the two. Both the Upper and Lower San Andres have distinct net-pay intervals on the order of 5-40 feet (2-13 m) thick (**Figure 3**).

Multicomponent Seismic Data Acquisition and Processing

During Phase-II of this study, the CO_2 injection program consisted of a miscible CO_2 flood involving six injection patterns around CVU producer No. 97; the location of a cyclic CO_2 injection test studied in Phase-I (**Figure 4**). A new baseline multicomponent seismic survey was acquired in December 1997, prior to the start of Phase-II injection, which began in April 1998. The monitoring survey was conducted in December 1998, eight months after the start of CO_2 injection.

During Phase-I, it became evident that the s-wave window was limited to a radius of half the depth to the objective. Beyond this window, offset s-wave polarizations are erratic. Based on this observation, sources were concentrated in the center of the survey while the geophone spread remained the same as for Phase-I. This change in acquisition geometry doubled the useable fold and greatly improved the quality of the s-wave data. The survey was also designed to take advantage of reusing about one quarter of the shots from the Phase-I monitoring survey for incorporation into the new Phase-II baseline survey. During the monitoring survey, a significant improvement in acquisition recording time occurred by using a cable telemetry system slaved to a radio telemetry system. Acquisition rates approximately doubled, giving hope that improved efficiency in field operations can reduce costs of multicomponent data acquisition while increasing, or at least maintaining, data quality. It is hopeful that this type of research will move into commercial use as costs are further reduced within the industry. The parameters of the Phase-II acquisition program are provided in **Table-1**.

The goal in processing is to produce the highest resolution with the best signal/noise ratio while maintaining the integrity of a 4-D processing environment. This goal was achieved through prestack noise attenuation, surface consistent deconvolution, and fold. The improved data quality in Phase-II resulted in better statics control, improved velocity picking, and better migrated stack imaging. The processing sequence for s-wave data is included in **Table-2**.

Static Reservoir Characterization

At CVU, the dominant reservoir heterogeneities include faults, micro-fracture zones, anhydrite-plugged zones linked to old fracture systems or karst development, and a layered reservoir architecture. Multicomponent seismic data has revealed the presence of faults with 10 to 20 feet (3 to 7m) of vertical offset at the reservoir level, which are not detectable from available wireline logs due to the diegenetic influences of porosity development relative to depositional environments. Due to the deposition of anhydrite, cataclasis, or offset of flow units, these faults cause partial sealing conditions to occur in the immediate vicinity. This observation has been substantiated by reservoir simulation, which requires that horizontal transmissivity be shut down or reduced between cells to history match individual well performance. On the positive side, these faults can act to bank hydrocarbons. This occurs mainly in the Upper San Andres because the flow units are thin and small amounts of vertical throw are sufficient to juxtapose flow units against flow barriers. As a result, hydraulic fracturing has been very attractive when confined to the Upper San Andres zones. Successful horizontal drilling efforts further support the faulting hypothesis.

Recurrent movements along these faults have created fracture zones in the reservoir. The greatest fracture density, as determined from s-wave splitting, occurs in proximity to the faults, and is highest where the faults bend to form areas of local stress relief. The open micro-fracture systems associated with these fracture zones act as conduits for vertical and lateral fluid movement in the reservoir.

S-wave amplitude analysis provides a high-resolution measure of s-wave splitting, which can be useful for resolving major flow units and deriving reservoir parameters in areas containing secondary porosity development. S-wave splitting can predict reservoir permeability when fractures or low aspect ratio pores are present. S-wave data is also advantageous for characterizing carbonate reservoirs having vuggy porosity (Davis, 1998). The term vuggy porosity, as used here, is related to the dissolution of original carbonate material to produce solution-enhanced fractures and molds. Vuggy porosity is important to reservoir characterization because it provides the storage capacity to feed fracture systems and enhances fluid produceability in many carbonate reservoirs. Vuggy porosity is better characterized by s-waves than p-waves because s-waves respond to reservoir rigidity, and the presence of vugs changes the rigidity of a medium dramatically.

The secondary porosity and vuggy nature of the reservoir at CVU allows for s-wave characterization of the higher permeability conduits. Large S_1 amplitudes correlate to high vuggy porosity in the San Andres reservoir. Inversion of the seismic data allows zones of high porosity to be delineated at approximately the same scale as petrophysically derived flow units. Interpretations of the time-lapse seismic inversion data indicate that these zones are conduits for fluid flow. P-wave seismic attributes were uncorrelated with well productivities, but high-resolution s-wave splitting parameters derived from s-wave AVO analysis (DeVault, 1997) provided an excellent correlation to well productivity

A petrophysical-based method was developed and utilized by Pranter (1999) to define flow units within the sequence stratigraphic framework. Flow units were based on vertical variations in flow-capacity and storage-capacity using log and core data. Larger pore throat radius intervals under capillary pressure tests corresponded to the zones of high flow-capacity and high storage-capacity. These zones had larger percentages of moldic and intercrystalline porosity types associated with fusulinid dolopackstones and sucrosic dolomite, indicative of dissolution enhanced secondary or vuggy porosity.

Flow units in cored wells were correlated across the characterization area in non-cored wells through logs to establish the reservoir framework. The framework was used to create a three-dimensional geologic model for flow simulation. The faults were introduced to the model from the seismic data and the multicomponent seismic data were used to distribute porosity and permeability in the interwell space. Flow simulation was conducted using this static reservoir model.

Reservoir simulation produced positive results, giving rise to changes in reservoir fluid properties in the same location as the seismic anomaly, thereby validating the potential for utilizing 4-D multicomponent seismic data to track miscible processes in the reservoir through seismic anisotropy monitoring. The simulation results matched the Phase-I cyclic CO_2 demonstration, showing changes in fluid properties (not pressure gradients) in the area of the seismic anomaly. The seismic anomaly of Phase-I was produced from a single well injection of 50 million standard cubic feet (scf) of CO_2 into the reservoir. The six-well injection program of Phase II introduced approximately 1 billion scf of CO_2 prior to the monitoring survey. The injection rates of Phase-II were designed to keep average reservoir pressure constant, so anisotropy anomalies would not be associated with effective stress changes.

Simulation showed that CO_2 movement occurred predominantly in specific flow units within the Lower San Andres. To meet the time frame for response based on the cyclic injection test in Phase-I and the six-well injection program of Phase-II, the permeability had to be increased in certain spatial areas. The most logical way of doing this was by adding contributions from fractures. In other words, the accelerated response of the actual flood to the simulation indicated that permeability needed to be enhanced between CVU 200 and CVU 97 to match the observed response time. Additional evidence for the presence of fractures comes from temperature surveys run in CVU 97. They suggest vertical movement of the miscible solvent or tertiary flood bank upward from the Lower San Andres; which is interpreted to be along fracture zones.

Dynamic Reservoir Characterization

Time-lapse effects are subtle, so the baseline and monitor survey(s) must be designed to maximize the signal-to-noise ratio of the data in addition to its repeatability. Because seismic anisotropy is the key to reservoir monitoring, it is essential to maintain high fold within the useable offset range. RCP used surface consistent linear processes, thereby preserving the integrity of the signal between the various surveys. Cross-correlation between common trace pairs in the interval above the reservoir was a powerful technique for matching various surveys (Roche, 1997). 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 1b). 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. Spatially, this anomaly matches the porosity and permeability trend in the reservoir. It also matches the fracture density map of DeVault (1997), suggesting a strong fracture control on the permeability. Carbon dioxide has a high mobility ratio and can move over relatively large distances, particularly within a fracture network. The observed anomaly infers that the tertiary flood bank contacts well CVU 97. Actually, first CO_2 response occurred in this well during October of 1998, two months before the seismic monitoring survey was conducted. Reservoir simulations completed before the current reservoir model had suggested it would be another 18 months before the well would be contacted.

The greatest need of tertiary recovery operations is to monitor and control the areal and vertical distribution of CO_2 in the reservoir to maximize contact with the oil and optimize sweep efficiency so that oil is not bypassed. In this study, 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 has to be handled 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.

Economic Impact

Dynamic reservoir characterization is evolving within the industry and has the potential to help maximize incremental recovery of both new and mature fields with a small increase in field operating costs that in many cases could be a fraction of the total production expenditures. The costs of dynamic reservoir characterization are offset by the ability to optimize development locations and increase productivity of existing wells by strategic completion (vertical or horizontal) in unswept compartments of the reservoir. The costs may be further offset by a corresponding reduction in the number of wells to be drilled. By providing a dynamic image of fluid and pressure changes in the reservoir, 4-D monitoring gives insights into field behavior, revealing the presence of sealing faults and bypassed oil. Such features are absent in predictions based on static models alone.

Possibly one of the greatest benefits of seismic reservoir monitoring is its ability to predict ahead in the framework of reservoir management. Many enhanced recovery processes are impaired or even rendered uneconomic once an adverse flowstream or breakthrough of injectant occurs. Reservoir production problems can be visualized with 4D seismology and compensated for early in the project's life, rather than reacted to after they have negatively impacted production. The greatest benefit of seismic reservoir monitoring, however, is increasing the recovery efficiency of a field. Advances in dynamic reservoir characterization technology has the ability to ultimately pay for itself through the additional percentage of incremental reserves that can be added through increased recovery efficiency.

If reservoirs can be monitored laterally and vertically by 4-D, multicomponent seismology, a reservoir can be more effectively managed. The corporate top line grows with increased recovery/revenues. Multicomponent 4-D seismology enhances the accuracy of reservoir models. An enhanced reservoir model enables improved forecasting, which allows for better operational response. Better operations, improved reservoir management, and associated production enhancement of this dynamic reservoir characterization technology has the promise of positively impacting the corporate bottom line.

Conclusions

The RCP has sponsored the world's first onshore multicomponent seismic investigation -- during the initial phases of a CO_2 tertiary recovery project. 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 (water and oil) with CO_2. Combining dynamic monitoring with simulation efforts allows for field operations adjustments to increase recovery efficiencies and improve project economics.

During the past two decades, 3-D seismology technologies have evolved significantly. Today, a similar evolution of the 4-D seismology technologies is a growing reality.

Acknowledgments

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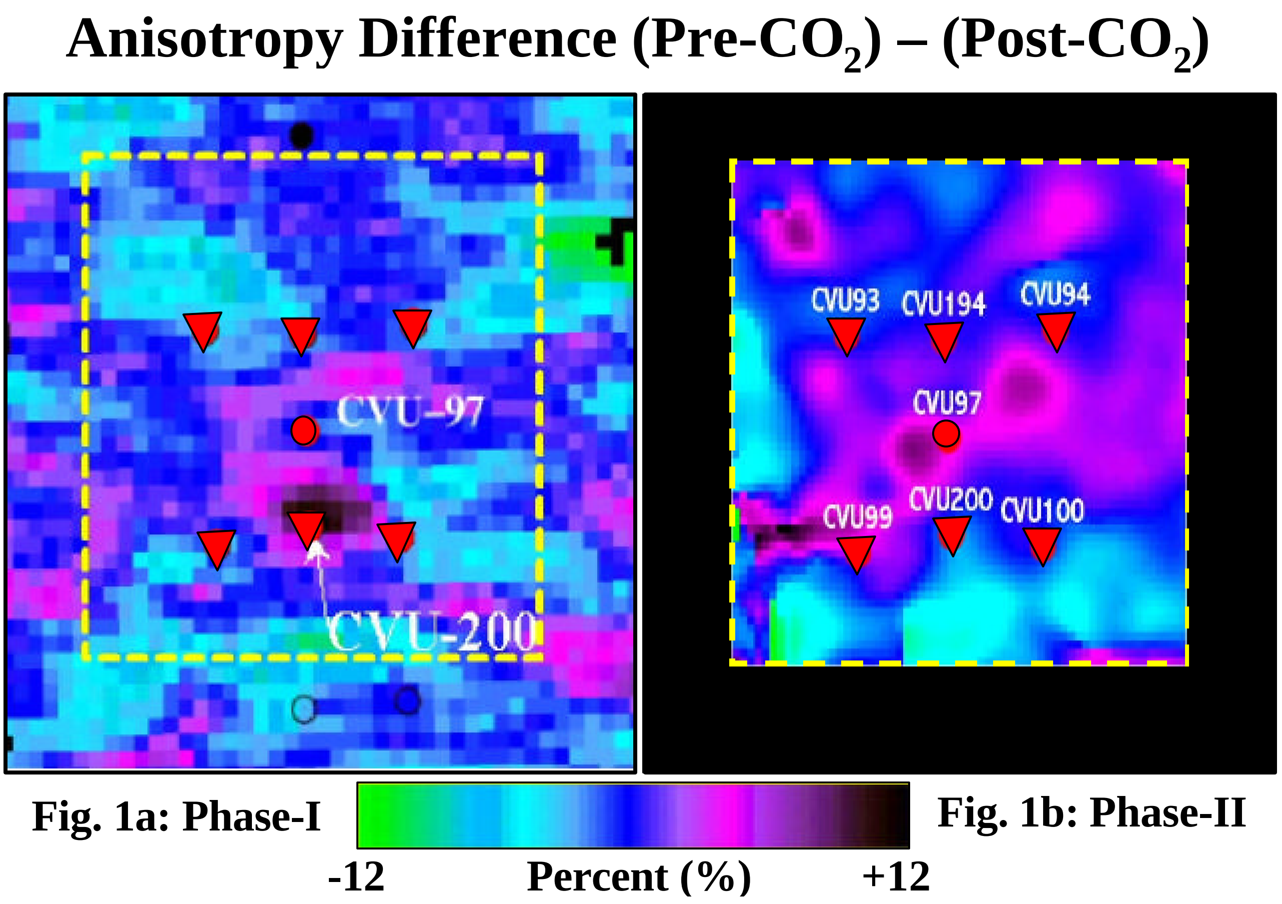

Figure 1. Time-lapse shear-wave velocity anisotropy difference. Phase-I CO_2 Injection occurred at the producer No. 97. Phase-II CO_2 Injection was at the six offset injectors (indicated by triangles).

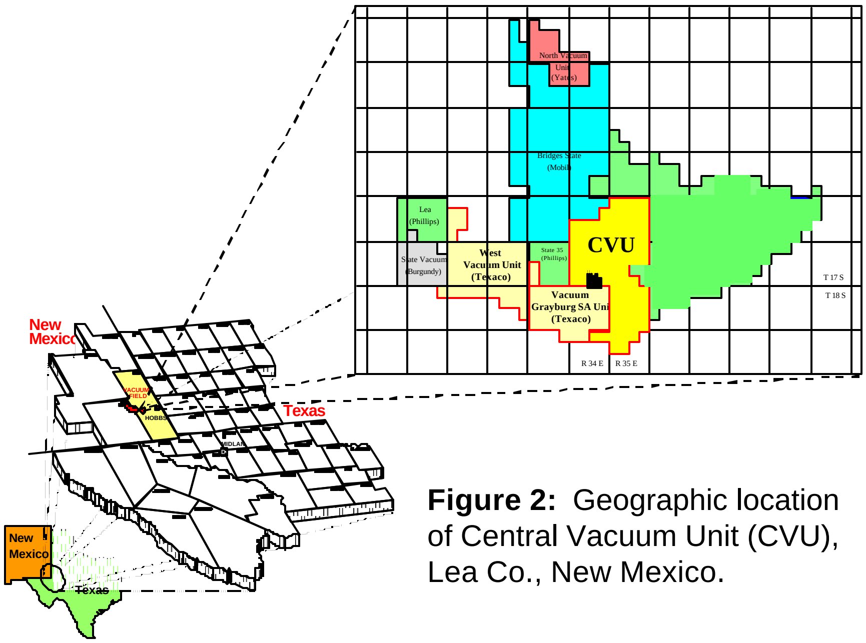

Figure 2: Geographic location of Central Vacuum Unit (CVU), Lea Co., New Mexico.

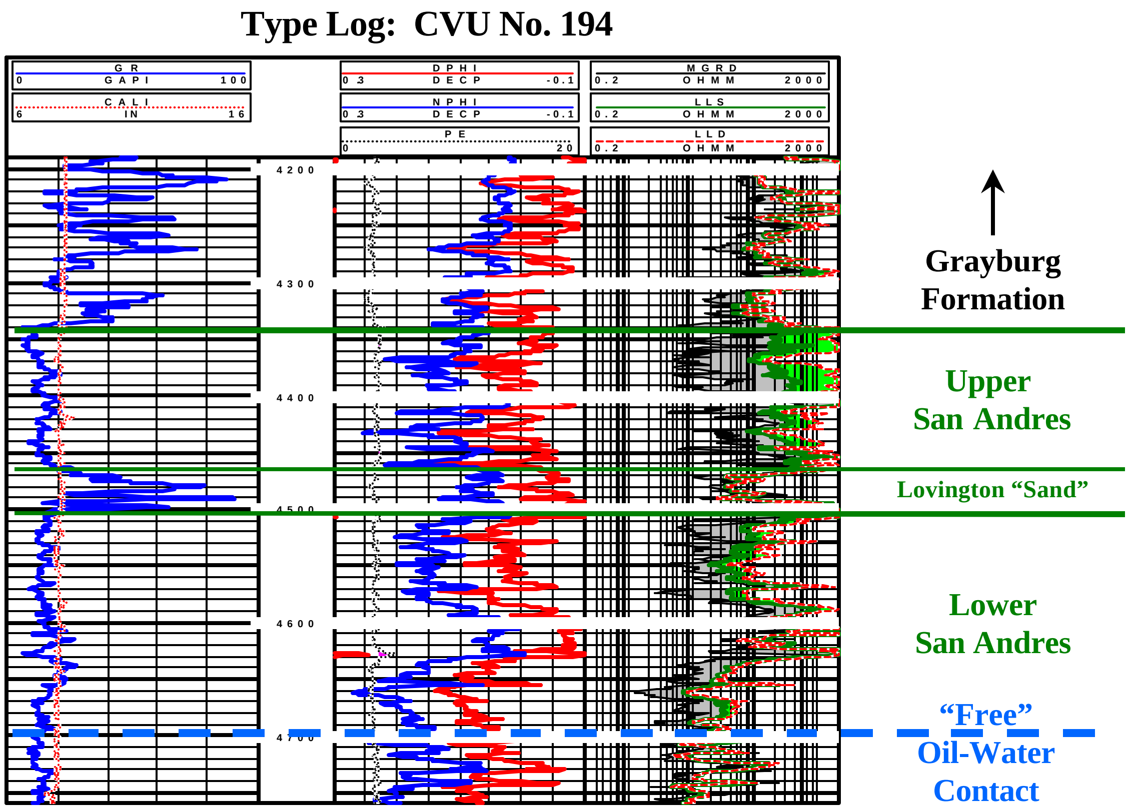

Figure 3: Typical wireline log character of San Andres formation at CVU. The Upper and Lower San Andres intervals are productive at CVU. The flow-capacity of the reservoir generally exists where porosity is greater than 7%.

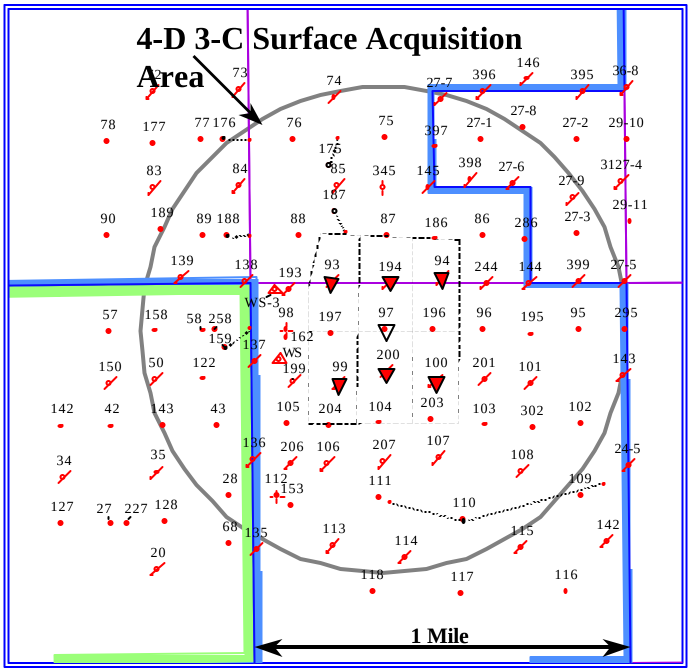

Figure 4: Layout of 4-D 3-C surface acquisition relative to local CVU flood patterns and wells. Phase-I involved injection of CO_2 at the producer No. 97. Phase-II monitored the CO_2 injection placed in the six offset injectors (indicated by triangles).

Table 1: Parameters of the Phase-II Acquisition Program

PARAMETER	PHASE-II
Type survey	3D, 3C (time lapse)
Covered Area	~1.5 sq. mile
Subsurface bin size	55 feet x 55 feet
Number of channels	2508
Number of source locations	774
Number of receiver locations	836
Total source point records	2322 (774 vert., 774 N-S horz., 774 E-W horz.)
Nominal/Effective fold (at the center of the survey)	~240 (all offsets)/~48 (0'<x<2400')
Type spread	Stationary: Circular pattern~7400 foot diameter
Instrumentation	I/O System II (MRX) 3rd SURVEY I/O System II (MRX and RSR) 4th SURVEY 2508 channels, 2ms sample rate 4 second correlated record length
Source interval/line spacing	110 feet / 150 feet, oriented E - W
Receiver interval/line spacing	110 feet / 495 feet, oriented N - S
Receiver array	3 elements, 3 foot spacing inline, 3C, 10 Hz geophones
Source array (P-wave)	Vertical vibrators: 2 units 8 – 120 Hz linear sweep, 10 sec duration 4 sweeps per location, no moveup Ground force phase lock
Source array (S-wave)	Horizontal vibrator: 1 unit per orientation (1 unit oriented N – S, 1 unit oriented E – W) 6-60 hz linear sweep, 10 second duration 6 sweeps per VP, 2 pad locations per VP Ground force phase lock

Table 2: Processing Sequence for Shear Wave Data.

BUILD IDENTICAL GEOMETRIES	NOTCH FILTER 30HZ NOISE FOR AREA RECEIVER
FOUR-COMPONENT ROTATION (ALFORD METHOD)	CONVOLVE RECEIVER DECONVOLUTION FILTERS
TRUE AMPLITUDE CORRECTION, TIME RAISED POWERS	RESIDUAL STATICS, 3RD PASS
SURFACE CONSISTENT SHOT AND RECEIVER AMPLITUDE	RESIDUAL SHOT STATICS, 4TH PASS
TRACE KILLS	NMO FINAL
SURFACE CONSISTENT SHOT AND RECEIVER FLATTENING STATICS	TOP MUTE
RESIDUAL STATICS, PASS 1 AND PASS 2	CROSS-CORRELATION OF COMMON TRACE PAIRS PRE AND POST PRESTACK TO MATCH SURVEY
NMO, 2ND PASS	CDP STACK
SHOT DOMAIN TX DIP FILTERING	FXY FILTER 8-50 MHz, 50% ADDBACK
RECEIVER DOMAIN TX DIP FILTERING	TXY FILTER REJECT MODEL, PASS REAL DATA
INVERSE NMO, 2ND PASS	CDP FOLD TAPER
BANDPASS BUTTERWORTH FILTER 6-18DB, 60-72DB	FINITE DIFFERENCE MIGRATION, VSP VELOCITY FIELD
MINI PHASE FILTER	