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Advanced Reservoir Characterization in the Antelope Shale to Establish the Viability of C02 Enhanced Oil Recovery in California's Monterey Formation Siliceous Shales

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By:
Michael F. Morea

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For
U.S. Department of Energy
Office of Fossil Energy
Federal Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Chevron USA Production Company (CPDN)
5001 California Avenue
Bakersfield, California 93309

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TITLE: **ADVANCED RESERVOIR CHARACTERIZATION IN THE ANTELOPE SHALE TO ESTABLISH THE VIABILITY OF CO2 ENHANCED OIL RECOVERY IN CALIFORNIA'S MONTEREY FORMATION SILICEOUS SHALES**

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Principal Investigator: **Michael F. Morea, CPDN**

Project Manager: **Jerry F. Casteel, Bartlesville Project Office**

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Objective

The primary objective of this research is to conduct advanced reservoir characterization and modeling studies in the Antelope Shale reservoir. Characterization studies will be used to determine the technical feasibility of implementing a CO_2 enhanced oil recovery project in the Antelope Shale in Buena Vista Hills Field. The Buena Vista Hills pilot CO_2 project will demonstrate the economic viability and widespread applicability of CO_2 flooding in fractured siliceous shale reservoirs of the San Joaquin Valley. The research consists of four primary work processes: Reservoir Matrix and Fluid Characterization; Fracture Characterization; Reservoir Modeling and Simulation; and CO_2 Pilot Flood and Evaluation. Work done in these areas is subdivided into two phases or budget periods. The first phase of the project will focus on the application of a variety of advanced reservoir characterization techniques to determine the production characteristics of the Antelope Shale reservoir. Reservoir models based on the results of the characterization work will be used to evaluate how the reservoir will respond to secondary recovery and EOR processes. The second phase of the project will include the implementation and evaluation of an advanced enhanced oil recovery (EOR) pilot in the West Dome of the Buena Vista Hills Field.

Summary of Technical Progress

Outlined below is a status report on the tasks that were performed during the 1st quarter of 1997.

Task A.1. Collect and Analyze Reservoir Data

Tasks A.1.A. New Tech. Production Logging & A.1.D. Old Tech. Production Logging

Chevron Petroleum Technology Co. independently evaluated the feasibility of using proposed new production logging tools and sensors. The following conclusions were reached.

PANEX Torque-Capacitance Memory Flowmeter*:* The PANEX torque-capacitance memory flowmeter was evaluated in a controlled field-trial in West Texas. The primary objective of this test was to generally characterize the PANEX flowmeter under controlled single phase conditions to verify instrument performance relative to PANEX specifications. A second goal was to determine the flowmeter's resolution for measuring low flowrates. Key conclusions from this study were: (1) The flowmeter has potential application in single phase, high rate environments such as injection wells; (2) Problems were encountered related to sensor hysteresis, thermal stability, time constants and resolution (PANEX is currently working on these problems); (3) Under controlled conditions, the flowmeter exhibited a linear response when rates exceeded 300 BWPD; however, below 300 BWPD, the instrument was unreliable; (4) The PANEX Torque-Capacitance flowmeter design is not robust and prone to downhole plugging; i.e., the shroud surrounding the spinner acts as a vena contracta causing debris to collect in the spinner metering chamber causing subsequent instrument malfunctions. The flowmeter shows potential; however, additional lab work is required to eliminate observed field problems. **At this time the flowmeter is not recommended for multiphase flow evaluation in producing wells at the Buena Vista Field.**

Halliburton Gas Holdup Tool (GHT*):* Chevron conducted the first field trial of Halliburton GHT (Gas-Holdup-Tool) at the East Painter Field on well 13-18A in Wyoming. The GHT was tested in a gas well producing with three phase flow. Although flow rates for East Painter Field well 13-18A were higher than those at the Buena Vista Hills Field, the nature of the flow problem is analogous to producing conditions at Buena Vista Hills. Under controlled field trial conditions, the GHT did not function properly. The GHT identically replicated the response of a backup, center-sample nuclear densitometer. Both tools utilize nuclear sources; however, operate on entirely different nuclear principles. The GHT did not maintain calibration from the beginning to the end of the survey. Halliburton could not explain or reconcile these discrepancies. Since the prototype field test, Halliburton has reported to have improved the GHT sensor performance; however, at this time, the tool has not been characterized under dynamic flow conditions to be credibly integrated in a combinable production logging tool stack to help improve downhole flow rate measurement. **Given the overall remaining effort to characterize and reevaluate the GHT, the sensor is not recommended for application at the Buena Vista Hills Field.**

Downhole Video Camera (DHV International & Halliburton): The downhole video camera has been extensively used in the evaluation of producing wells throughout Chevron's worldwide operations. Wells have been logged under static and dynamic conditions. Logged wells have production rates comparable to Buena Vista Hills wells. The downhole video camera has been found to be most effective when: wellbore fluid clarity exists; flow rates are not turbulent; water is the continuous phase; gas rates are low; segregated flow exists; mechanical problems (casing inspection) are expected; scale is present. Lastly, the camera must be deployed in such a way as to be able to log under typical producing conditions. Chevron's experience has been positive when using the downhole video to view wellbore fluids under shut-in conditions; however, downhole video has limited utility when wells are actually logged under dynamic flowing conditions. Fluid clarity is the key to effective camera application. Wells 553-26B and 554-26B of the Buena Vista Hills Field (Section 26-T31S/R23E) are interesting examples of downhole video fluid entry surveys that illustrate how shut-in video surveys are effective for detecting fluid entries. Flowing surveys were ineffective as fluid clarity was poor. This information provides a compelling rationale for developing effective production log methodologies for logging rod-pumped wells.

Video Logging in 563-26B and 564-26B Wells Under Shut-In Condition: Video logs were run in two Buena Vista Hills wells, the 563-26B and 564-26B, on March 13, 1997. The principal objective of these surveys was to identify gas and oil entry into the wellbore. A secondary objective was to identify possible holes or leaks in the casing that warrant remedial attention.

The 563-26B well was producing 1/5/20 O/W/G prior to shutting in to prepare for video logging. This well held only 10 psi wellhead pressure after having been shut-in for two weeks. The fluid level in the well was at 3052'; above the top of the slotted liner at 3938'. Gas bubbling was moderate to strong above 4318' (in the P interval) and disappeared below 4318'. No oil entry was observed in the well. A water shutoff hole or leak was observed in the 8 5/8" casing at 1054'. Leaks were also observed at the top of the 6 5/8" slotted liner at 3897'.

The 564-26B well was producing 3/60/10 O/W/G prior to shutting in to prepare for video logging. This well held no wellhead pressure after having been shut-in for two weeks. The fluid level in the well was at 3264'; above the top of the slotted liner at 3845'. Gas bubbling was observed to be moderate to strong as deep as the video logging tool could be lowered, down to a scale obstruction at 4566' (in the P1B interval). Very light oil entry and oil-stained slots were observed at 3986' - 3991' (in the N interval). Four water shutoff holes were observed in the 6 5/8" protective string at 3015'. A possible hole or crack was observed in the 6 5/8" slotted liner at 4555'.

Task A.3. Perform Core Analysis

Task A.3.A. Wettability Testing - Laboratory

The cleaning process has now been completed on all nine samples. Samples taken from depths of 3989.2', 4315.6' and 4355.95' have all been saturated with brine and are now in the centrifuge for the forced water drainage stage of the testing. The remaining six samples are also ready for brine saturation. Note that samples from depths of 4040.9', 4288.2' and 4679.3' are the least permeable of the nine samples with the sample taken from a depth of 4040.9' being the tightest of the samples. This particular sample might not be testable.

Task A.3.L. Specific Permeability

All 15 samples have been cut at the requested depths. Core Laboratories are in the process of shipping all 15 plugs to their laboratory in Houston for the NMR scan (T1/T2) testing phase.

Task A.3.O. Core Imaging

Core photography in white light and ultraviolet light has been completed using a format of 18' per print. Five sets of prints and a photo CD were delivered in the 4th quarter of 1996. The photo CD has been further used to analyze the ultraviolet images to quantify lithology and pay intervals on a small scale for integration in a core-log transform. Using Core Laboratories' Imagelog^{tm} software, the ultraviolet images were converted into binary images with the pay intervals being integrated to determine net pay in the cored interval. This task is completed except for issuing the final report.

Task A.4. Fracture Characterization

Task A.4.A. Shear-Wave Birefringence VSP

A nine-component VSP survey was recorded in well 653Z-26B, Buena Vista Hills Field on Nov. 14-16, 1996, primarily for the purpose of evaluating stress and fracture effects as a function of depth, and help characterize the natural fracture system. This data would then be used to predict the orientation of hydraulic fractures should well 653Z-26B be fracture-stimulated in the future. Analysis of the VSP data was completed in March, 1997 and indicated strong shear-wave (S-wave) birefringence in upper formations but negligible birefringence through a thick zone at the bottom of the well (3330' - 4830') that includes the Brown Shale and the Antelope Shale. The polarization azimuth of the fast shear (S) wave was about N25° E in the uppermost anisotropy layer but oscillated about due north in deeper layers. Birefringence in the uppermost layer exceeded 12 percent. It then diminished appreciably but reached 5.1 percent just above the zone of negligible birefringence. Several anisotropy features of the Buena Vista Hills VSP resemble other VSP surveys recorded earlier in the nearby Elk Hills and Railroad Gap Fields.

The negligible birefringence in the Brown and Antelope shales implies that these rocks are isotropic (the fractures are randomly oriented). **Thus, the VSP data indicates that there should be no preferred direction for hydraulic fractures to propagate.**

Task A.4.B. Cross-well Seismic Acquisition and Processing

Acquisition of four crosswell profiles in the Buena Vista Hills study area was completed during March, 1997 using the TomoSeis system. On average it took about 3.5 days to collect each profile, though future projects should see this reduced due to operational efficiencies learned during the project. In each of the profiles, a 5-level receiver string was placed in well 653Z-26B which provided a quiet environment for recording (the well is cased but not yet perforated). TomoSeis' piezoelectric source was placed successively in each of 4 surrounding producers. These wells produce from slotted liners in the Brown Shale and Antelope Shale and are known from recently obtained video logs to have gas entry (and therefore bubbling) in the recorded interval. Nevertheless, this did not seem to have a major impact on data quality as the latter ranged from fair to outstanding, with the primary factor affecting quality being the well spacing.

The size of each of the surveys ranges from about 35,000 to 70,000 traces. The data have surprisingly high frequency content (300 Hz - 2000 Hz) and are extraordinarily rich in *P*-wave reflection events with wavelengths on the scale of 10 ft. The data obtained in the 563 to 653Z and 564 to 653Z profiles are superior to the other two surveys (553 to 653Z and 554 to 653Z) and may be the best ever obtained by Chevron. **The results from these surveys should allow for the construction of the first (ever) high resolution, crosswell reflection images of San Joaquin Valley sediments.**

There are three types of crosswell images that can potentially be obtain from these data, depending on data quality. The first image type, a velocity image (traveltime tomography), serves as the baseline for time-lapse imaging and monitoring of any future EOR processes. It is also needed for reflection imaging, and can serve as a slightly lower resolution substitute for a sonic log between wells. The second image type, a reflection image, is much like that obtained from 2-D surface seismic data, except that it has at least an order of magnitude greater resolution. It can be used for reservoir characterization and possibly detection of fluids in high permeability zones (using "bright spot" technology). The third image type, an attenuation image (attenuation tomography), has the largest research component associated with it. It is hoped that attenuation images can be used to assess fracture density. Attempts will be made to generate all three image types using the Buena Vista Hills dataset.

The following table (Table 1) summarizes Bob Langan's (Chevron Petroleum Technology Co.) impressions for the processing potential of each crosswell profile. His impressions are based upon field observations and may be modified after further processing of the data.

Table 1. Potential For Obtaining Different Types of Crosswell Images.

Profile	Horizontal Distances	Velocity Imaging	Reflection Imaging	Attenuation Imaging
553-653Z	520 to 800 ft	Excellent	Good	Good
563-653Z	520 to 690 ft	Excellent	Excellent	Very Good
564-653Z	440 to 670 ft	Excellent	Excellent	Excellent
554-653Z	570 to 830 ft	Good	Fair to Poor	Fair to Poor

Note: The horizontal distances cover the range in well spacing in the Upper Antelope and Brown Shale.

In each of the four profiles (Table 1), about 60% of the survey coverage was obtained with the source in slotted liner while the rest was obtained through casing. The spectral content of the data acquired in the slotted liners is different from that recorded inside the casing in all but one of the profiles. (For an unknown reason, the 564 - 653Z profile did not produce the distinctly different data characteristics in the slotted liner versus the casing, resulting in the most balanced of the four data sets.) A strong effort will, therefore, be made to handle this variability by balancing the spectral content of the two data types. While this represents a new data-processing challenge, good results are anticipated and are in fact critical for the attenuation imaging and the reflection imaging.

Table 1 shows that in terms of reflection imaging, it is anticipated that two of the profiles (563 - 653Z and 564 - 653Z) will produce excellent images with complete well-to-well coverage. The “good” rating for the 553 - 653Z profile, in Bob Langan’s opinion, indicates that it is more likely that a partial reflection image will be obtained between the two wells (two offset vertical seismic profiles (VSP’s) which would image out to a distance of 200’ from each of the end wells). The “fair to poor” rating for the 554 - 653Z well profile indicates that Bob is very uncertain what result will be obtained by processing the data for a reflection image.

Task A.4.D. High Resolution Structural Mapping

During the 1st quarter, the OpenWorks database was completed for the Buena Vista Hills Field. With the loading of about 90 additional wells, it now contains a complete set of around 250 wells that penetrate the Brown Shale and Antelope Shale. Data for these wells includes surface locations, directional surveys, and digital open-hole logs.

At the end of the quarter, work was nearly complete on correlating formation marker tops in the Brown Shale and Antelope Shale sections using StratWorks. A total of 7 Brown Shale and 15 Antelope marker tops were being correlated and a list of observed fault cuts were being tabulated. Structure maps are expected to be finalized in the second quarter of 1997. These will be used as input to the 3D earth model that will also be constructed during 1997.

Task A.4.E. Core Fracture Analysis

Atilla Aydin and Judson Jacobs of Stanford University have started preliminary work on the core fracture analysis. It is their opinion that there are many fractures of tectonic origin. Judson will be returning in the 2nd quarter to begin his detailed analysis which will form the basis of his Master thesis.

Task A.4.H. Regional Tectonic Synthesis

As part of the Fracture Characterization task, Advanced Resources International (ARI) is conducting a Regional Tectonic Synthesis of the southern San Joaquin Basin, including the Buena Vista Hills Field. The study area extends from near the Wheeler Field (south of Buena Vista Hills) northward to the Lost Hills Field, and covers much of western Kern County. Ned Mamula and David Campagna of ARI describe their progress below.

The work conducted during the past quarter included: 1) completion of Part I of the Regional Tectonic Synthesis (Synopsis of Previous Investigations), and 2) initiation of Part II of the study (Natural Fracture Detection). For Part II of the tectonic synthesis, we have identified the remote imagery data sets available to us for the southern San Joaquin Basin/Buena Vista region, acquired some, and have begun to analyze the data in order to compose structure maps. This work will continue and be completed during the next quarter.

One finding we made based upon our review and critique of the literature has to do with fault-fracture relationships within the Monterey Formation. Despite all the information gathered on Monterey rocks in the San Joaquin Basin and elsewhere in central California, there is still not a clear or consistent understanding regarding the character of the fractures and their relationship to faulting. Relatively few areas of surface-exposed faulting and associated fractures are available for detailed examination within the San Joaquin Basin. Some investigators have observed that highly fractured areas and intervals are not genetically related to folding or faulting, citing that some wells drilled into anticlines or close to faults frequently fail to find adequate fracture permeability and porosity in the Monterey Shale.

Also, suitable fracture porosity and permeability are often erratically distributed on productive anticlines of Monterey and not present in the hinge line of folds or in the vicinity of faults. Many fractures in Monterey rocks, however, display systematic fracture orientations implying that the fractures did not develop in a hydrostatic stress field, and are more likely associated with faulting than with diagenesis. For example, it has been postulated that early-formed oriented fractures may have developed at shallow depth due to dewatering, coupled with faulting and gravity-induced down slope extension. However, recent work on fault/fracture relationships has shown evidence for fault-related fractures, and that these types of fractures are possibly due to bedding slip during folding.

It can be argued that faulting controls hydrocarbon migration and production in the Buena Vista Hills Field and surrounding fields especially where they evolve, from a preexisting discontinuity, forming a highly fractured or brecciated zone, along which migration occurs. These types of bed-parallel (and bed-perpendicular) faults have been observed and well documented throughout the Monterey Formation. The key to their existence is undoubtedly due to the tectonic deformation that occurred in this region during latest Miocene to Pliocene to Pleistocene to Recent, when the southwestern San Joaquin Basin experienced uplift, and crustal shortening due to thrust faulting and anticlinal folding. The overall configuration of folds and faults in the Monterey indicates extensive crustal shortening (compression) of between 12 and 17 percent in a N30 - 40E direction.

The importance of diagenesis cannot be overlooked because diagenetic overprinting of fractured rocks may “heal” fractures, as observed in chert and porcelanite horizons according to the work of Snyder (1987), suggesting that the timing of deformation and diagenesis has a great deal to do with the production control. Another scenario thought to occur in Monterey rocks is localized tectonic fracturing superposed upon preexisting diagenetic structures, creating a maximum of interconnected fracture permeability, and an increased level of tectonic control of production. Undoubtedly the control of Monterey Formation production is affected by all of these processes. It would appear that the occurrence and post-diagenetic timing of tectonic deformation would have the most influence on economic production, and would be the most favorable model in terms of future exploration in the Buena Vista Hills Field and elsewhere in the San Joaquin Basin.

Finally, as a result of our literature research efforts, we realized that despite the enormity of the geological literature on the San Joaquin Basin, there appears to be relatively little published information on the Buena Vista Hills Field and surrounding area. Unpublished information on the Buena Vista Hills Field structure, reservoir and production has generously been made from Chevron, and we are currently in the process of obtaining this information for use in Part II of our investigation.

Task A.4.K. Attenuation Imaging

This task involves analyzing the cross-well image data for attenuation imaging to identify fracture density. Though data acquisition was completed by early March 1997, Stanford University did not receive a copy of the data until after the 1st quarter. They expect to start their analysis in April.

Task A.7. Develop 3D Earth Model

Task A.7.B. Geostatistically Populate Model

Efforts were begun late in the quarter to assess correlations between open-hole logs and core data. More than 95% of the wells in the field have limited open-hole log data (usually 1950's - 1960's vintage electric logs with SP's only). Initial efforts are focusing on the correlation of SP logs to core porosity and permeability. If a good correlation can be established, it will be used to geostatistically model one of these petrophysical properties in order to populate the 3D earth model.

Task A.7.C. Visualize Reservoir Property Distribution

Dale Julander and Dale Beeson obtained Stratamodel training at the Landmark training center, Houston in March 1997. Stratamodel will be used to build the 3D stratigraphic framework across the Buena Vista Hills Field. Dale Beeson also organized a best practices demonstration at Chevron Overseas Petroleum Inc. in San Ramon incorporating both Stratamodel and GOCAD UNIX applications into workflows that allow for the use of each application in reservoir characterization and visualization.

Task B.1. Re-evaluate Pre-1994 Production Performance

Task B.1.C. Analyze Recovery, Pressure and Saturation Data

A reservoir engineering database continues to be constructed using a Chevron propriety database.

Task B.2. Initiate Fluid Characterization and Lab Displacement Tests

Task B.2.C. Water Flood Displacement Tests of Sand Samples

All nine samples have been cut at the requested depths. Core Laboratories will commence the cleaning process as soon as the core holders become available.

Task D. Technology Transfer

Work is proceeding on oral presentations to be given at the May, 1997 Pacific Section AAPG/SEPM Convention in Bakersfield, CA. The session titled "Reservoir Characteristics and Improving Recovery in Monterey-type Siliceous Shales" will be presided by Bruce Bilodeau and Steve Smith of Chevron. Also Mike Morea and Tom Zalan of Chevron, and Jud Jacobs of Stanford University will speak at a convention short course titled "Advances in Reservoir Description Techniques, as Applied to California Oil and Gas Fields".