DOE/BC/14941-15
(OSTI ID: 14232)

ADVANCED OIL RECOVERY TECHNOLOGIES FOR IMPROVED RECOVERY
FROM SLOPE BASIN CLASTIC RESERVOIRS, NASH DRAW BRUSHY
CANYON POOL, EDDY COUNTY, NM

Quarterly Technical Progress Report
July 1, 1998-September 24, 1998

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Report Issue Date: October 1, 1998

Performed Under Contract No. DE-FC22-95BC14941

Strata Production Company
Roswell, New Mexico

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Advanced Oil Recovery Technologies for Improved Recovery from Slope Basin Clastic
Reservoirs, Nash Draw Brushy Canyon Pool, Eddy County, NM

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November 1999

Work Performed Under Contract No. DE-FC22-95BC14941

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QUARTERLY TECHNICAL PROGRESS REPORT
(12th Quarter)

**ADVANCED OIL RECOVERY TECHNOLOGIES FOR IMPROVED
RECOVERY FROM SLOPE BASIN CLASTIC RESERVOIRS,
NASH DRAW BRUSHY CANYON POOL, EDDY COUNTY, NM**

DOE Cooperative Agreement No. DE-FC-95BC14941 -15

14232

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Date of Report:	October 1, 1998
Award Date:	September 25, 1995
Anticipated Completion Date:	September 24, 1998 - Budget Period I September 25, 2001 - Budget Period II
Award Amount for Current Fiscal Year:	\$1,080,432
Award Amount for Budget Period I:	\$3,354,067
Name of Project Manager:	Mark B. Murphy
Contracting Officer's Representative:	Mary Beth Pearse
Reporting Period:	July 1, 1998-September 24, 1998

Dan Ferguson

US/DOE Patent Clearance is not required prior to the publication of this document.

OBJECTIVE

The overall objective of this project is to demonstrate that a development program—based on advanced reservoir management methods—can significantly improve oil recovery at the Nash Draw Pool (NDP). The plan includes developing a control area using standard reservoir management techniques and comparing its performance to an area developed using advanced reservoir management methods. Specific goals are (1) to demonstrate that an advanced development drilling and pressure maintenance program can significantly improve oil recovery compared to existing technology applications and (2) to transfer these advanced methodologies to oil and gas producers in the Permian Basin and elsewhere throughout the U.S. oil and gas industry.

SUMMARY OF TECHNICAL PROGRESS

This is the twelfth quarterly progress report on the project. Results obtained to date are summarized.

Seismic Attribute Analysis

A development option for the Nash Draw Pool (NDP) is a targeted drilling program. In Quarterly Technical Progress Reports #9-11, the potential value of geostatistical techniques for estimating interwell reservoir properties, with infill drilling as a possible goal, was discussed. However, NDP wells primarily cover the center part of the available seismic survey, so a new technique was developed to extrapolate reservoir properties beyond the area directly constrained by wells.

Multivariable Regression for Reservoir Properties: "K" and "L" Intervals

The new technique utilizes a non-linear multivariable regression using seismic attributes as inputs and porosity, water saturation, and net pay as outputs. The regression equations allow us to predict these three reservoir properties in areas without direct well control, and to compute related maps such as $\phi \cdot h$ and $h \cdot \phi \cdot S_o$.

Data

The two primary sources of data required for this method are well data and seismic attribute data. The well data used in this study are tabulated in Table 1. Over 80 seismic attributes were extracted from the NDP seismic data volume for the two horizons using the PostStack and Pal tools of the Landmark Graphics seismic interpretation suite. Extracted attributes were averaged across the entire interval of both the "K" and "L" horizons, respectively, and the well data from each of the 19 wells used in the study were also averaged across the respective intervals. Thus the output maps presented later in this report represent interval-averaged values for the respective reservoir properties.

Table 1
Well and seismic attribute analysis

<u>Well</u>	<u>"K" Net</u> <u>Pay</u>	<u>"K"</u> <u>Porosity</u>	<u>"K" Sw</u>	<u>"L" Net</u> <u>Pay</u>	<u>"L"</u> <u>Porosity</u>	<u>"L" Sw</u>
U-1	40.5	5.9	80.8	35.5	10.1	41.7
U-5	65.0	8.7	87.3	31.0	10.5	59.1
U-6	44.5	11.1	87.9	25.0	13.4	41.4
U-9	63.5	8.7	88.7	31.5	7.2	76.1
U-10	47.0	10.2	91.1	14.5	12.5	43.2
U-11	37.0	10.9	81.3	28.0	12.8	37.9
U-12	59.5	9.1	90.9	46.5	11.3	53.6
U-13	52.5	12.3	70.1	38.5	13.6	40.6
U-14	45.0	11.5	72.9	26.5	13.1	42.5
U-15	39.0	10.8	93.3	28.0	13.7	40.3
U-19	67.5	4.2	93.6	19.5	12.4	39.9
U-20	22.5	12.6	84.6	20.5	13.1	47.8
U-23	34.5	10.5	79.0	6.5	13.0	38.8
U-24	52.5	11.8	75.1	23.0	12.9	47.7
U-25	35.0	11.2	81.5	12.0	9.2	88.5
U-29	52.5	11.7	92.7	31.5	12.1	42.1
U-38	57.0	14.3	96.5	23.5	11.0	97.0
T-FEE-1	56.5	8.5	98.2	43.0	10.7	75.4
T-FED-1	71.0	6.6	99.4	67.0	10.5	75.9

Attribute Selection

It is computationally infeasible to use all of the extracted attributes in individual non-linear regressions for reservoir properties; therefore, we used a fuzzy-ranking algorithm to select attributes that are best suited for predicting individual reservoir properties. The algorithm statistically determines how well a particular input (seismic attribute) could resolve a particular output (reservoir property at the wellbore) with respect to any number of other inputs. Each attribute is assigned a rank, which allows a direct estimation of which attributes would contribute the most to a particular regression.

The fuzzy ranking algorithm was applied to select the optimal inputs (attributes) for six

output cases: “K” porosity, “K” net pay, “K” water saturation, “L” porosity, “L” net pay, and “L” water saturation.

Multivariable Non-linear Regression

Linear regression for reservoir properties was not feasible for this study, as the relationships between input and outputs were poorly defined by individual attributes. We elected to use a non-linear regression using the fast-converging, feed-forward, back-propagation conjugate gradient algorithm (neural network) implemented in-house at the PRRC. Two neural network architectures were used in the study, both of which were minimized in order to maintain a satisfactory ratio of training data to weights (coefficients of the regression equation). The two networks are graphically illustrated below.

In these architectures, circles represent “neurons”, or locations of non-linear functions, while each line represents a coefficient applied to these equations. A back-propagation feed-forward algorithm such as the conjugate gradient algorithm used, is “trained” using known inputs and outputs. For this study, we have reservoir properties that are known at the locations of the wellbore intersections with the interval of interest. We also have seismic data that covers a much larger area,

and also have data at the locations of the wellbore intersections. Seismic attribute data from the same seismic bin that contains the well is correlated to wellbore values of porosity, net pay, or water saturation in an iterative process using the neural network. Table 2 shows which attributes and network were used in regressions for each reservoir property in the two intervals of interest.

Table 2
Average interval attributes used for the non-linear regressions

Reservoir Property	Architecture	CC	Attributes
"K" Porosity	Network 1	0.89	Max peak frequency Avg absolute frequency Isochron
"K" Net-Pay	Network 2	0.86	Max peak frequency Avg absolute frequency Avg absolute amplitude Isochron
"K" Water Saturation	Network 1	0.83	Avg reflection strength Avg peak frequency Isochron
"L" Porosity	Network 1	0.88	Isochron Avg instantaneous frequency Energy half-time
"L" Net Pay	Network 1	0.80	Avg max peak amplitude Avg RMS amplitude Avg Peak amplitude
"L" Water Saturation	Network 1	0.84	Avg instantaneous phase Avg trough amplitude Energy half-time

Training and Testing

It is customary to test the robustness of a solution by holding some data out for testing. Since we have only 19 control points, we elected to train our networks using all 19 points, and then test by removing sets of three wells, retraining the network with 16 control points, and then using that network to predict the three withheld points. We applied this exercise three times for each property and interval, withholding differing sets of three points for each test. **Figure 1** shows the results of training with all 19 points, and three test sets for the "L" interval porosity regression. It is evident that the network has resolved porosity in a robust fashion, and that the tool may be used to predict porosity in other areas of the field. **Figure 2** shows the 19 point networks for the other reservoir

properties of the “L” and the “K” intervals. These regressions were also tested in the same manner, and had similar results.

Predicting Fieldwide Reservoir Properties

The regression relationships (architecture and weights) were used to compute maps of fieldwide porosity, net pay, and water saturation, which were displayed in Landmark’s SuperSeisworks Map view. Screen images of these properties, and computed ϕ^*h and $h^*\phi^*So$ maps are presented in Figures 3-7. In general, these maps fit expectations based on other geostatistical techniques and reservoir understanding.

Discussion of Maps

For each of the map sets in Figures 3-7, the same color bar was used, though ranges may vary slightly. Therefore these maps highlight relative differences between the “K” and “L” intervals.

Figure 3 shows “K” and “L” interval porosity maps predicted using our regression relationships. Both “K” and “L” horizons show patterns of distinct, or isolated porosity, and the “L” porosity map compares favorably with compartment maps produced independently. Figure 4 shows “K” and “L” interval net pay maps. The “K” horizon shows much more variation in pay than the “L” zone, which is reasonable considering that the “K” interval is discontinuous and may pinch out, while the “L” interval is considered to be reasonably continuous across the study area. Lineations in the NW corner of the “L” net pay map may indicate facies changes, or onlap deposition and subsequent compartmentalization. Figure 5 shows “K” and “L” interval water saturation maps. In general the “K” interval appears to be wet, except in distinct pods, which may represent possible drilling targets. The “L” interval is not as wet as the “K”, but distribution is more uniform, though an area of high water saturation in the NW corner, which is up-dip, may be due to compartmentalization as indicated in Figure 4.

Figures 6 and 7 show ϕ^*h and $h^*\phi^*So$ maps for the “K” and “L” horizons. The ϕ^*h maps in Figure 6 are useful as an indicator of where sufficient pay porosity exists within the field. The “K” horizon shows a good deal of variability, with relatively lower ϕ^*h in areas where the “K” zone is interpreted to pinch out. The “L” interval ϕ^*h illustrated in Figure 6b shows a more uniform distribution of pay porosity, though some thinner and thicker areas do exist. Fine detail across the middle portion of the map may assist in determining compartmentalization of porosity, as net pay is relatively uniform across that region. The hydrocarbon pore volume maps in Figure 7a and 7b for the “K” and “L” intervals, respectively, include information on oil saturation ($1-S_w$) and essentially illustrates where the oil is located in the field. The wet “K” interval shows only isolated pods of good production potential, while the less wet “L” interval shows strong undrilled potential production in the SE quadrant of Section 11, the SW and NW quadrants of Section 7, and the west half of Section 14.

Geology and Engineering

The production database was updated through July 1998. These data were added to the history of each well to update the decline curves and to project ultimate recoveries as well as to assess the effects of interference and production strategies.

Data are being compiled in response to the Technical Data Request made in February 1998. It is anticipated that the project data and TORIS data will be submitted at the conclusion of Budget Period #1.

A Project Evaluation Report, plan for Phase II, statement of work, and Phase II budget were prepared and submitted in August 1998. Phase II is proposed to include directional/horizontal drilling and early pressure maintenance to develop reserves under surface-restricted areas and potash mines in order to enhance the ultimate recovery from the project.

Recent Seismic Interpretations

The basal Brushy Canyon interval is deposited on the top of Bone Spring depositional surface, which influences the quality of the reservoir and the continuity of the individual sands. To further understand the importance and origin of the depositional surface for the basal Brushy Canyon sandstones at the NDP and enable the extrapolation of this information to other areas, a 10,000-foot interval from the Cherry Canyon to the Morrow formation was investigated. In addition to the seismic interpretations of the "K" and "L" pay intervals in the Brushy Canyon formation at the NDP, recent seismic interpretations have been extended to include the Morrow, Bone Spring, and Cherry Canyon formations.

3-D Seismic Interpretation of Morrow System

The position of the Morrow in the NDP 3-D seismic data volume was estimated by extending the time-vs.-depth trend of the VSP data in NDP Well #25 to a depth of 13,000 ft, which is the assumed depth of the Morrow formation at the NDP. This assumed depth equates to a 3-D seismic image time of approximately 1.75 sec. Four sets of displays were prepared to describe the seismic interpretation of the Morrow system.

Initially the vertical profiles and time slices through the unflattened 3-D seismic data volume were reviewed. NDP Well #25, the VSP well, is located at trace coordinate 132 and line coordinate 58 (Landmark software notation) of the seismic image space. The vertical profiles follow these inline and crossline well coordinates. The position of the Morrow formation (Figure 8) is shown as a tick mark on the section view. Inspection of the 3-D data showed that there was a reasonably continuous, good quality reflection peak approximately 30 ms above the calculated position of the Morrow formation. This overlying peak was interpreted across the complete data volume and was used as a reference surface for the Morrow interpretation. This reference surface is labeled 1710 ms *horizon* on the vertical section. There is evidence of Morrow faulting in this section view and in map views. The time slices pass through the assumed Morrow section. In these horizontal views, faults appear as linear disruptions in reflection amplitude.

The 3-D data were flattened on the 1710 ms reference horizon for the north-south profile 132 and east-west profile 58. Also on these vertical sections are two surfaces 20 ms and 50 ms below the 1710 ms reference surface that are conformable to the reference surface. The data window between these two surfaces spans the Morrow system. A number of time slices were cut through this Morrow-dominated data window to determine if any depositional patterns, such as stream channels, could be discerned. These time slices are reasonable approximations of Morrow-age stratal surfaces. No depositional patterns are obvious on these slices; however, fault trends are easier to see on these constant depositional-time surfaces than on the time slices through the unflattened data volume. North-south fault systems were identified, and each trend is manifested by a linear disruption in reflection amplitude.

Figure 9 is a time structure map of the 1710 ms horizon. This map will be assumed to be equivalent to a Morrow depth map until there is adequate well control and velocity control to modify the structural configuration. Various attributes were calculated over the 30-ms data window that spans the Morrow system. The attributes that were analyzed were maximum peak amplitude, maximum trough amplitude, energy half time, average instantaneous frequency, average reflection strength and the ratio of positive to negative amplitude. This data window is sufficiently narrow that any seismic attribute that reacts to Morrow deposition should reveal areal patterns of Morrow stratigraphy. No attribute shows a depositional pattern that is particularly intriguing. Almost every attribute shows some type of discontinuity that is related to the faults that have been described previously.

Reflector continuity at the Morrow level was analyzed. Changes in reflection continuity indicate faults and stratigraphic terminations such as pinchouts and channel boundaries. Linear fault trends were depicted rather well, but no depositional pattern occurs that would suggest the presence of a Morrow channel system.

3-D Seismic Interpretation of Bone Spring Formation

The structural and stratigraphic characteristics of the Bone Spring formation in the NDP area were examined. The database consisted of 3-D seismic data, well data, and sidewall core analyses.

The top of the Bone Spring is represented by a high amplitude peak with approximately 20 ms of relief, ranging from about 978 - 998 ms (Figure 10). The pick is highest in the west and has two low areas, the first of which is more or less N-S and runs through the eastern part of Sections 11 and 14. The second low is approximately NE-SW going from Section 7 to Section 13.

The origins of the subtle structural features of the Bone Spring at the NDP are probably multiple. The observations indicate that the same structural trends that are observed at the top of the Bone Spring are present, but accentuated, at the level of an unidentified seismic reflection at approximately 1500 ms TWT (two-way travel time). However the trends are not present at the level of an unidentified seismic reflection at approximately 300 ms TWT. These observations, and examination of the time structure maps from the Bone Spring suggest that structuring that might be associated with deformation generally increases with depth in this area.

It is believed that the main structures at the Bone Spring level in this area are the expression of subtle relative movement on basement blocks during the Permian period. Initiation of structure development began in the Pennsylvanian period, a time of tectonic activity during which the Central Basin Platform was raised. Tectonic activity, including reactivation of basement features, was probably less intense in the NDP area because it is relatively far removed from the deformation front. Structure development continued but decreased during the Permian period, so that, by the end of the Leonardian series (top of Bone Spring) and into the early Guadalupian series (lower Brushy Canyon), subtle structures continued to influence depositional patterns.

Simultaneous examination of the 3-D seismic and log data from the NDP indicates that the Avalon Sand is detectable in the seismic data as a discontinuous peak approximately 16 ms below the Bone Spring seismic pick. This conclusion is supported by the results of the seismic modeling at Sand Dunes South, which showed that the Avalon sand should be identifiable as a seismic event approximately this distance below the Bone Spring pick.

The structural configuration of the Bone Spring Formation at the NDP and the stratigraphic and seismic character of the Avalon Sand at the NDP and the Sand Dunes South Fields were examined. The two main findings are:

- 1) Movement along basement features is thought to be the main factor affecting the current structural configuration of the Bone Spring Formation. This movement is thought to have decreased throughout the deposition of the Bone Spring, but influenced deposition of the Avalon Sand and so may have influenced deposition of the basal Brushy Canyon Formation as well.
- 2) The Avalon Sand can be detected seismically, and the thickness of the porous section can be determined from seismic attributes. This unit is productive where channelized (e.g., at Sand Dunes South) but has not yet been found to be productive at the NDP, where the sand is more sheet-like. It may be that depositional processes, influenced by syn-sedimentary structural development, exert a primary control on reservoir quality. In this case, the Avalon interval may not be prospective in the NDP area or, if it is, the thicker parts of the Member should make the best reservoir.

3-D Seismic Interpretation of Cherry Canyon System

Data was analyzed that explains the 3-D seismic interpretation of the Cherry Canyon system. The horizon at about 560 ms in each vertical section is the reference stratal surface from which the Cherry Canyon interpretation was done (Figure 11). This surface is associated with a robust reflection peak that extends over the total 3-D image area, and it should be reasonably conformable to stratal surfaces with the Cherry Canyon. Two surfaces are found at 26 ms and 56ms, respectively, below the reference surface at 560 ms. Both surfaces are conformable to the reference. These two horizons bracket the Cherry Canyon reservoir facies that was positioned in the 3-D seismic image space by the VSP time-vs-depth control from NDP Well #25. The horizon that is midway between the 26 ms and 56 ms surfaces passes through the Cherry Canyon position at NDP Well #24 (which was defined to be at a depth of 4200 ft) and is conformable to the Bone Spring horizon almost 400 ms deeper in the image space (the Bone Spring is below 1.0 sec and is not shown in any of these vertical sections). This midpoint horizon was not used in the Cherry Canyon interpretation. It was

shown to emphasize the fact that seismic stratal surfaces more than 3000 ft apart vertically and on opposite sides of the Cherry Canyon system (one above and one below) are reasonably conformable. The conclusion was that a narrow data window that brackets the Cherry Canyon system could be constructed by using either the Bone Spring horizon (at about 1000 ms) or the horizon at about 560 ms as a reference stratal surface. The better choice of the two reference horizons is the one that is closer to the Cherry Canyon target, which would be the horizon at 560 ms. All Cherry Canyon interpretation was done using data window boundaries that were conformable to this 560 ms horizon.

The position of the Cherry Canyon reservoir facies in the 3-D seismic image at NDP Well #24 is critical for determining which reflection peak or trough is associated with the thinbed unit. The waveform characteristic that is genetically related with the Cherry Canyon facies position at a depth of 4200 ft is the reflection peak that is midway between the 26 ms and 56 ms below the reference surface.

Cherry Canyon reservoirs are seismic thin-bed units as are the Brushy Canyon "K" and "L" reservoirs that have been interpreted previously. Using the guidelines established in the Brushy Canyon work (and in other seismic thin-bed studies), the amount of net pay in the Cherry Canyon section should increase as the amplitude of the associated reflection peak increases. Consequently, the seismic attributes that should indicate Cherry Canyon drill sites would be those that react to this seismic reflection peak amplitude within the data window bounded by the 26 ms and 56 ms horizons.

Appropriate amplitude-sensitive attributes that should indicate Cherry Canyon net pay were considered: maximum peak amplitude, average peak amplitude, average absolute amplitude and average reflection strength. These attributes show that the amplitude peak associated with the Cherry Canyon facies at NDP Well #24 increases in elliptical areas that trend southwest-northwest and are located west and north of NDP Well #24. Equally robust amplitude behaviors occur in a large area spanning NDP Wells #1, 5, 6, 10, 20, and 29. However, this latter area of increased amplitude responses creates a false indication of Cherry Canyon net pay and is associated with a different depositional sequence than the sequence that creates the Cherry Canyon facies at NDP Well #24 and west and northwest of NDP Well #24.

Two sequences were identified, sequence A being the one that is genetically related to the attractive Cherry Canyon facies in NDP Well #24, and sequence B being the one genetically related to the less attractive Cherry Canyon facies, found in the eastern wells. There is no way to tell from the seismic data alone which sequence has the more attractive net pay possibilities. However, once well control defines which depositional sequence is preferred, then the 3-D seismic data can be used to map the areal amplitude behavior in the targeted sequence.

Seismic Conclusions

Several conclusions can be drawn from this portion of the seismic work.

Deep, Morrow-related faults appear to have a genetic relationship to the bench-step model that is being used to describe Brushy Canyon deposition.

The top of the Bone Spring Carbonate reflects the deep structure and provides the depositional surface for the Basal Brushy Canyon interval.

The bench-step sequence is carried through to the shallow Cherry Canyon interval in the upper Delaware.

A north-south bench running through Sections 12 and 13 and a step running north-south through Sections 11 and 14 is evident at each stratigraphic level.

Advanced Log Analysis

The test version of the Advanced Log Analysis program for predicting potential productive zones in the Delaware is being programmed. After testing and verification, this program will be available for distribution.

Technology Transfer

Transferring technical information generated during the course of this project is a prime objective of the project. Toward this objective, Strata has participated in several meetings and workshops to promote the dissemination of information from the project. A summary of technology transfer activities during this quarter is outlined below.

Phase I Project Report: A complete report of Phase I activities is being prepared along with the Third Annual Report.

Internet Homepage: The new address of the Website for the Nash Draw project is: <http://baervan.nmt.edu/REACT/Links/nash/strata.html>. This site includes an interactive map of logs and production data for the project and the most recent annual (second annual) report including graphics.

During this quarter, PRRC personnel made presentations of results of the research from the Nash Draw project involving the correlation of 3-D seismic attributes with well properties and capturing 3-D seismic images from 2-D seismic lines. These presentations were made in Dallas, Ft. Worth, Midland, and Odessa, Texas to more than 80 individuals in 14 companies representing major oil companies and independent producers. Comments from the various company meetings indicate that interest in 3-D seismic attribute analysis is universal to both majors and independents.

Fig. 1a.

Fig. 1b.

Fig. 1c.

Fig. 1d.

Fig. 1. Crossplots for the L-zone porosity, final and test regressions. 1a) Shows the crossplot for training with all 19 well control points. 1b) The network was retrained excluding points 17-19, which were then predicted using the network (purple points). 1c) The network was retrained excluding points 9-10, which were then predicted using the network (purple points). 1d) The network was retrained excluding points 1-3, which were then predicted by the network (purple points).

Fig. 2. Crossplots for training the K interval porosity, net pay, and water saturation; L interval net pay and water saturation.

Fig. 3a. Predicted K porosity.

Fig. 3b. Predicted L porosity.

Fig. 4a. Predicted K net pay.

Fig. 4b. Predicted L net pay.

Fig. 5a. Predicted K Sw.

Fig. 5b. Predicted L Sw.

Fig. 6a. Predicted K ϕ_h

Fig. 6b. Predicted L ϕ_h

Fig. 7a. Predicted K h ϕ So

Figure 7b. Predicted L h ϕ So

Fig. 8. Morrow level faults.

Fig. 9. Morrow time structure map.

Fig. 10. Bone Springs time structure map.

Fig. 11. Cherry Canyon time structure map.